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EXPECTED PERFORMANCE OF THE GLOBAL BROADCAST SERVICE (GBS), PHASE II, WITH EMPHASIS ON ENVIRONMENTAL LIMITATIONS TO SUPPORTABLE DATA RATES

by

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The US military requires a high capacity, high availability broadcast capability to provide timely dissemination of standard products to users who cannot rely on terrestrial links. The Global Broadcast Service (GBS) is being developed to meet this requirement. The key limiting factor in GBS availability is environmental losses, specifically atmospheric absorption and rainfall loss. The optimum frequency band for GBS would have been between 1-10 GHz. At this frequency range, environmental losses are negligible. However, congestion in this frequency range has forced DoD to choose a much higher frequency band for GBS, 20/30 GHz (K/Ka band). At this frequency band environmental losses, specifically rain loss, will be a key limiting factor to GBS availability. This thesis analyzes GBS Phase II performance taking into account atmospheric limitations. A key problem in determining the performance of GBS lies in the accuracy of existing rain loss models. Several rain loss prediction models were considered, and based on studies conducted by the ITU-R and Stanford Telecom, the USA rain model was chosen for this analysis. This thesis has shown that, due to environmental losses, high availability can best be achieved if GBS is capable of lowering its data rate during periods of precipitation.

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ABSTRACT

The US military requires a high capacity, high availability broadcast capability to provide timely dissemination of standard products to users who cannot rely on terrestrial links. The Global Broadcast Service (GBS) is being developed to meet this requirement. The key limiting factor in GBS availability is environmental losses, specifically atmospheric absorption and rainfall loss. The optimum frequency band for GBS would have been between 1-10 GHz. At this frequency range, environmental losses are negligible. However, congestion in this frequency range has forced DoD to choose a much higher frequency band for GBS, 20/30 GHz (K/Ka band). At this frequency band environmental losses, specifically rain loss, will be a key limiting factor to GBS availability. This thesis analyzes GBS Phase II performance taking into account atmospheric limitations. A key problem in determining the performance of GBS lies in the accuracy of existing rain loss models. Several rain loss prediction models were considered, and based on studies conducted by the ITU-R and Stanford Telecom, the USA rain model was chosen for this analysis. This thesis has shown that, due to environmental losses, high availability can best be achieved if GBS is capable of lowering its data rate during periods of precipitation.

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EXECTUTIVE SUMMARY

The US military requires a high capacity, high availability broadcast capability to provide timely dissemination of standard products to users who cannot rely on terrestrial links. The Global Broadcast Service (GBS) is being developed to meet this requirement. The key limiting factor in GBS availability is environmental losses, specifically atmospheric absorption and rainfall loss. The optimum frequency band for GBS would have been between 1-10 GHz. At this frequency range, environmental losses are negligible. However, congestion in this frequency range has forced DoD to choose a much higher frequency band for GBS, 20/30 GHz (K/Ka band). At this frequency band environmental losses, specifically rain loss, will be a key limiting factor to the data rate deliverable by GBS. This thesis analyzed supportable data rates for the GBS Phase II package aboard UFO's 9 and 10 considering worst case atmospheric losses for four significant regions of the world: Korea, the Mediterranean, the Caribbean, and the Persian Gulf. The atmospheric losses considered were those expected for August, when in the northern hemisphere, water vapor content is at its highest. The analysis also considered the UFO satellite at its furthest distance from the receiver in its daily orbital drift. Because of orbital drift, atmospheric losses can vary by more than 1 dB in a 24 hour period.

A key problem in determining the performance of GBS lies in predicting rain loss. A number of rain loss prediction models have been developed. However, these cannot be used to correlate attenuation to a particular rain event. Instead these models try to predict a level of signal attenuation due to precipitation for an average year. These models provide an estimated margin required to close the link for a given percentage of availability. Typically, a 99% or better link availability is desired. A key deficiency of the models currently in use, in particular the Crane Global model and the CCIR model, is that they were developed prior to the wide spread use of K/Ka-band RF links. There exists a body of experimental data to confirm attenuation at C and Ku bands. But data at K/Ka band frequencies are scarce. Existing prediction models appear to lose their robustness when applied to K/Ka band frequencies. Several rain loss prediction models were considered for determining expected rain loss for GBS. Based on studies conducted by the ITU-R and Stanford Telecom, an unpublished rain loss prediction model, the USA rain model, was selected for this analysis. Though this

model proved to be the best available it still has a high RMS error: 39.6% for K-band and 32.18% for Ka-band.

Using the USA rain model, this thesis developed link budgets for the four regions considered in order to determine the data rate GBS will support for a 99% link availability. Two receivers were considered for analysis. The first receiver considered had a 22 inch antenna and a 1.4 dB receiver noise figure, giving it a 16 dB/K figure of merit. The second receiver had an 18 inch antenna and a 2.5 dB receiver noise figure, giving it a 12.5 figure of merit. This thesis showed that GBS will be able to support close to the maximum data rate for the higher figure of merit receiver for all the regions considered except the Caribbean for 99% of an average year. However, the lower figure of merit receiver was not able to support the maximum data rate for any of the regions for at least 99% of the time. The higher figure of merit receiver requires an antenna which may be too large for most of the Navy's smaller ships. Moreover, 1.4 dB noise figure receiver is expensive, estimated to cost $25K per copy. This cost may limit the number of these receivers available to the military.

Therefore, to maximize GBS availability, the military will need to incorporate an ability to reduce the data rate of GBS to ensure link closure for those units not having a 16 dB/K receiver. Whether GBS will be able to vary its data rate will ultimately depend upon the transmission standards selected. Three options are being considered for GBS: the European Digital Video Broadcast standard (DVB), the Hughes Corporation Direct Satellite System (DSS), or a standard developed specifically for GBS. DSS doesn't have the capability to vary the transmitted data rate. A standard developed specifically for GBS will add additional development cost to the system. DVB, having a capability to vary its data rate and being an open standard, appears to be a good choice for GBS.

I. GBS - INTRODUCTION

A. BACKGROUND

The current military communications satellite constellation is oversubscribed and is not designed to deliver high volume, continuous information to multiple users. To supply this high volume, continuous information flow, DoD needs a satellite system with high bandwidth. Fixed users such as in-garrison units can rely on terrestrial links to satisfy their need for high volumes of information. However, a user on the move such as deployed ships cannot rely on terrestrial links. "For clarity, a user on the move is defined by U.S. Space Command as a user whose receiver must function while he is moving, necessitating the use of an antenna which can track a satellite." [Ref. 1:p. 2] In today's joint operating environment, deployed battlegroups need the same access to information as their land-based counterparts.

Commercial industry has developed the capability to broadcast a high volume of data via very small antennas and affordable receiving equipment. This technology is readily adaptable to military needs. The technology embodied in commercial direct broadcast service (DBS) can be modified with additional DoD investment to serve the needs of the military user on the move [Ref. 11:p. 1]. The effort to modify and incorporate DBS technology is the concept of a Global Broadcast Service (GBS). The development and deployment of GBS is to be accomplished in three phases.

> Phase I (FY96-98) -- Limited Demonstration: Leased commercial satellite transponders operating at Ku-band, used for concept of operations development, demonstration, and limited operational support. Transponders are being leased on two satellites: Orion I for service to IFOR in Bosnia and SBS-6 for the CONUS GBS CONOPS development broadcast.
>
> Phase II (FY98-00+) -- Interim Military Satellite Capability: Initial fielding of GBS packages on UFO 8, 9 and 10. Acquiring user terminals and information management systems. Integration of GBS with Defense Information

Infrastructure (DII) and complete connectivity with various providers of high-volume information.

Phase III (FY00-02+) -- Objective System: Fielded systems will be upgraded with objective requirements with satellite constellation that will provide worldwide coverage. Complete integration with GCCS and other intelligence broadcast and theater information management systems.

GBS will be a system of information sources, up-link sites, broadcast satellites, and receiver terminals as well as management processes for requesting and coordinating the distribution of information products. Each GBS satellite will be served by a primary up-link site where information products are assembled and up-linked to a high-powered satellite for relay to forces over a large geographic area. This primary up-link site will be known as a Primary Injection Point (PIP). To put into context what is meant by a high power satellite, consider that DSCS satellites are equipped with two 40-watt and four 10-watt transponders. The GBS Phase II satellite package will have four 130-watt transponders. In addition to the primary up-link site, the GBS satellite will be served by a theater up-link site, known as the Theater/Tactical Injection Point (TIP). GBS will be able to provide high-volume data directly to small (18-24 inch), mobile antennas, giving forces on the move access to data formerly accessible only to in garrison forces. [Ref. 11:p. 2]

There is much excitement and anticipation over the potential capabilities of GBS. This should be tempered as there will be difficulties with the GBS system that were not seen with other DoD communications satellites. The optimum band for GBS would have been in what is called the "noise window." The "noise window," between 1 - 10 GHz, is where galactic and man-made noise are minimum. [Ref. 5:p. 493] However, congestion in the 1 - 10 GHz region and DoD bandwidth (BW) allocation has forced DoD to choose a higher band, the 20/30 GHz radio frequency band (K/Ka band).

K/Ka band offers three advantages for satellite communications: larger BW allocations (at K/Ka band, 1 GHz BW is common); smaller probability of harmful interference such as jamming; and smaller equipment size. The benefits of the Ka band are not without drawbacks. The 20/30 GHz band is more susceptible to atmospheric

impairments than the bands of lower frequencies. [Ref. 8] Impairments to space-to-earth communications at Ka-band caused by atmospheric phenomena, especially rain, is a major challenge which the GBS system design must address if it is to provide the high availability currently enjoyed with Fleet Broadcast (FLTBCST) via the UHF satellites.

In addition to rain fade considerations, the operational user must understand the coverage limitations of the system. There is a large difference between the GBS satellite's access area (the area that is in view of the satellite) and its coverage area (the area covered by its transmit beams). The access area can be determined by the following equation:

$$\text{IAA (Instantaneous Access Area)} = 2\pi Re\,[1 - \cos(\lambda)] \tag{1.1}$$

where:

$\cos(\lambda) = [Re/ (Re + h)]$, angular radius from the satellite,

Re (radius of the earth) = 6378 km,

h = satellite altitude,

Re + h is the semi-major axis, r, of a satellite.

r is determined by the below equation:

$$r = ((P/2\pi)^2 \times \mu)^{1/3} \tag{1.2}$$

where P is the satellite's orbital period and μ is the gravitational constant of the earth, 3.986×10^5 (km^3/s^2). For a geosynchronous satellite, the orbital period P is 1 sidereal day (23hr 56 min 4 sec) and r is 42,164 km.

The IAA for UFO 8, 9 and 10 will be about a third of the earth or over 134 million square miles, each. However, each of these satellites offer just two spot beams and one wide area coverage beam, with nominal diameters of 500nm and 2000nm, respectively. This equates to approximately 3.5 million square miles coverage. Figure 1.1 shows the coverage limit for the GBS package aboard UFO 8 and the edge of the two spot beams, the first centered at Seoul and the second centered at San Diego, and the edge of the area coverage beam centered at Seoul. Though the UFO GBS coverage beams are steerable, there is a limit to how far the beam can be slewed in a day. Understanding the limitations of GBS will foster realistic expectations of the GBS and enhance efficient use of the system.

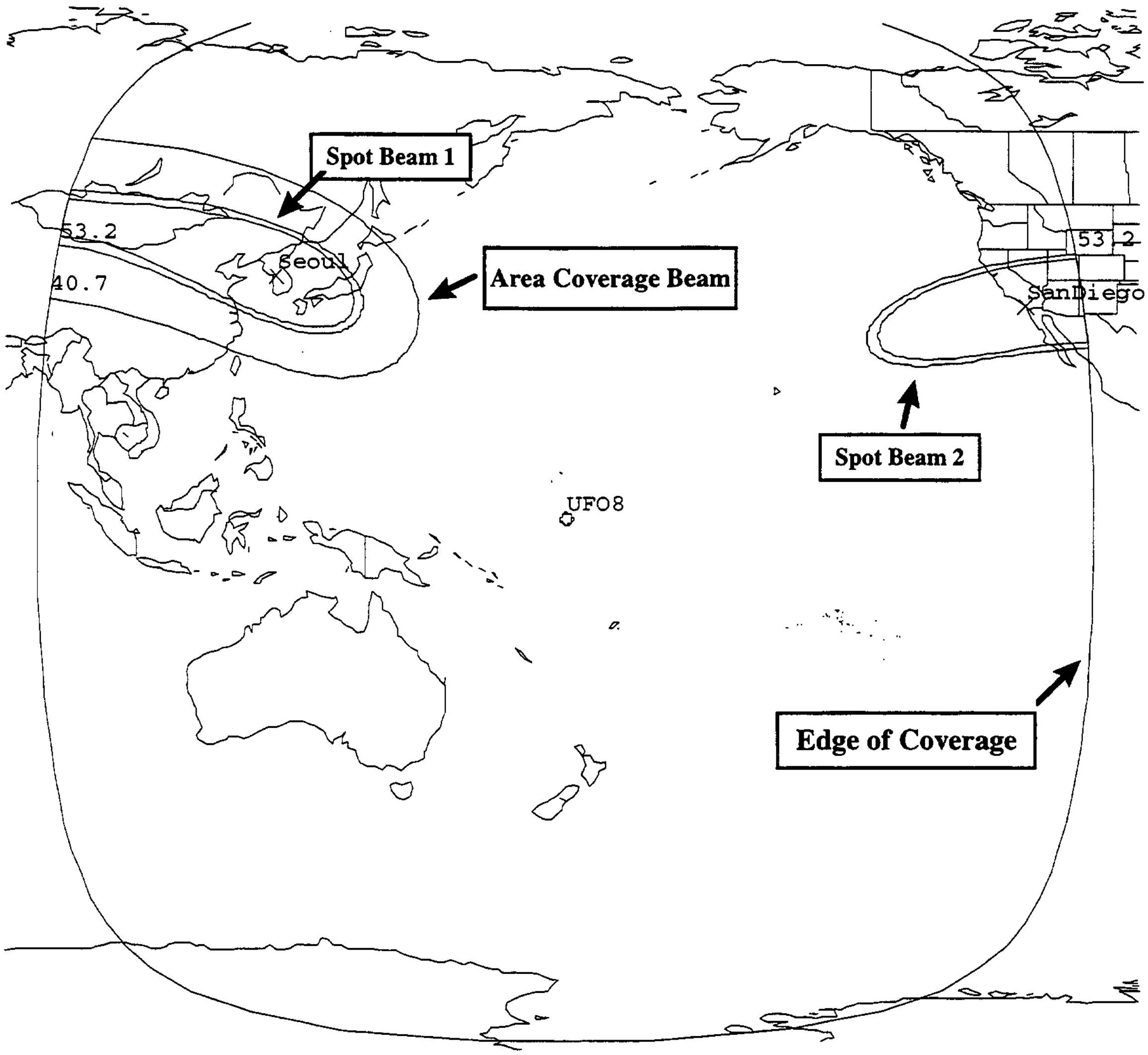

Figure 1.1: GBS UFO 8 IAA

This thesis will focus on the expected performance of GBS Phase II, with emphasis on environmental limitations to the data rates GBS can deliver. Before discussing GBS's limitations the Phase II system will be described in detail.

B. GBS PHASE II SYSTEM ARCHITECTURE

GBS will provide broadcast services to selected echelons through a fully scaleable architecture. GBS components will be common and modular. This architecture will compensate for differences in security classification levels and classes of users, and the

way in which users receive information products. GBS will complement existing communications systems, support open system protocols, and be integrated as part of the DII.[Ref. 7: p. 9]

Figure 1.2 depicts a simplified functional flow of information from the data sources, through the GBS, and into the operating environment of the end user. The products received by the GBS are delivered by electronic transmission via satellite and are often disseminated by local area networks to end-users of the GBS data. The receive broadcast manager and the end users can communicate additional needs through other channels back to the data sources or to the transmit broadcast manager. The DII information manager and the Theater Information Managers (TIM) provide overall management of the information flow through GBS.[Ref. 7:p. 9]

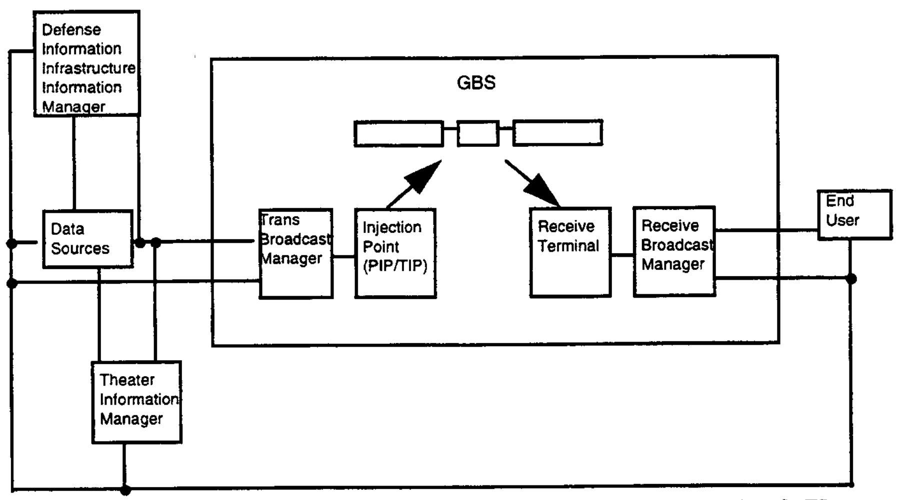

Figure 1.2: Simplified GBS Functional Flow [From Ref. 7]

The GBS Phase II architecture consists of the following segments and functional elements: Space Segment; Broadcast Management Segment; Terrestrial Communications segment; Terminal Segment; and Receive Suite. [Ref. 7:p. 9]

1. Space Segment

The primary element of the Space Segment is the GBS payload hosted aboard UFO 8, 9 and 10. This will relay scaleable multi-megabit video and data products. The UFO/GBS frequency allocation is 30-31 GHz for the up-link and 20.2-21.2 GHz for the down link. The up-link signal is provided by the PIP and TIP (refer to Figures 1.2 and

1.3). Each UFO/GBS satellite will have four 130-Watt transponders, two up-link antennas and three down-link antennas (see Figure 1.3).[Ref. 7:p. 10]

The general configuration plan for the UFO GBS package is as follows: Receive antenna 1 is fixed, and designed to receive the PIP up-link. Antenna 1 will feed transponders 1, 2 and 4. Receive antenna 2 is steerable, and is designed to be flexible enough to receive TIP up-links from anywhere within the satellite access area. It will feed transponder 3. Transponders 1 and 2 will feed two 24 Mbps broadcasts into a spot beam, nominally 500nm in diameter. These data streams will be transmitted via transmit antenna 1. Transponder 4 will feed the 1.544 Mbps (T1) broadcast into a wide area beam, nominally 2000nm, and transmit it via transmit antenna 3. However, this transponder can also transmit on antenna 2. Transponder 3 is reserved for the theater up-link, provided via the TIP. This broadcast is 6 Mbps and is also a nominally 500 nm spot beam. This broadcast is received via receive antenna 2 and is transmitted via transmit antenna 2. The actual frequencies (in GHz) for each transponder are as follows:

Transponder 1: 30.095 (up-link) - 20.295 (down-link)
Transponder 2: 30.215 (up-link) - 20.415 (down-link)
Transponder 3: 30.275 (up-link) - 20.475 (down-link)
Transponder 4: 30.395 (up-link) - 20.595 (down-link).

All the GBS transmit antennas are left hand circularly polarized.

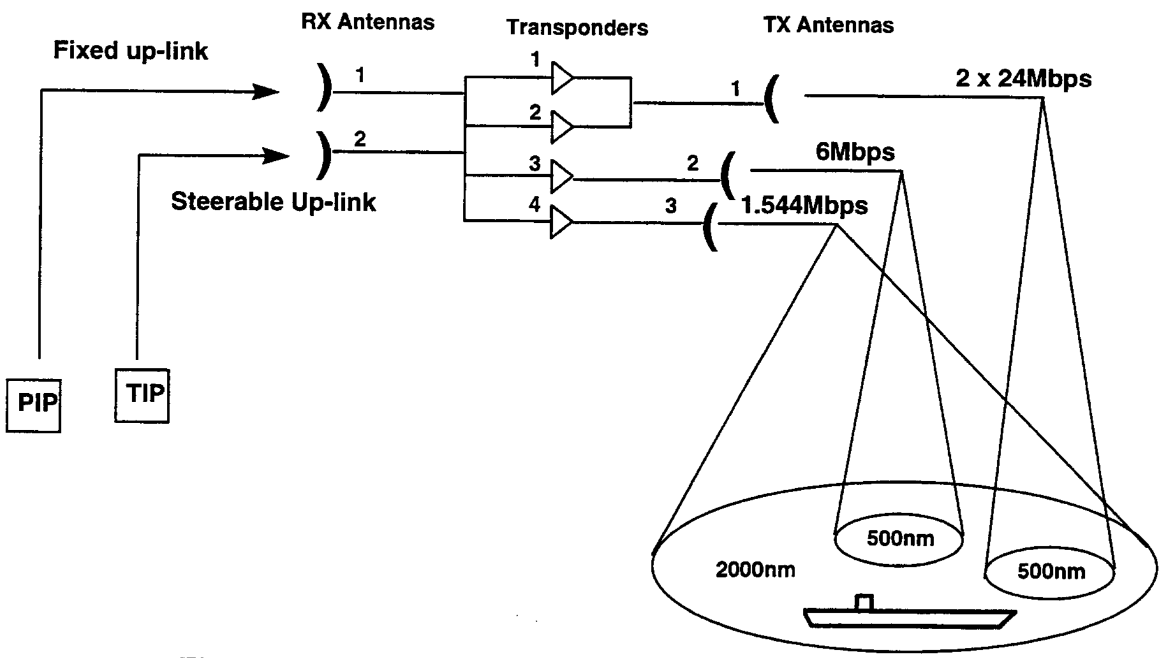

Figure 1.3: Simplified GBS antenna/transponder configuration

2. Broadcast Management Segment

The Broadcast Management Segment consists of the Transmit Broadcast Management (TBM) element and the Receive Broadcast Management (RBM) element (refer to Figure 1.2). The TBM can be further divided into regional satellite broadcast management and theater broadcast management. The TBM builds the broadcast data streams and manages the information flow to the appropriate injection point(s) for transmission to the satellite(s). This is accomplished by multiplexing the various inputs via time division multiplexing (TDM) into a single data stream. These inputs can be divided into general broadcast products, smart push products, and user pull products. Once this information is multiplexed, it is ready to be transmitted to the PIP/TIP. The PIP/TIP and the TBM element do not need to be collocated. The RBM functions to support the dissemination of the information from the terminal receive element. This involves demultiplexing the incoming data stream into individual channels.[Ref. 7:p. 10]

3. Terrestrial Communications Segment

Terrestrial Communications (TC) Segment includes furnished communications resources to support the transfer of high band-width data between the PIP, TBM elements, major Defense Information System Network (DISN) nodes and other government networks.

4. Terminal Segment

The GBS Terminal Segment consists of the UFO/GBS PIPs, TIPs, and the Receive Terminal element. The primary function of the Terminal Segment is to support radio frequency (RF) communications with the GBS Space Segment. The PIPs will up-link information received from the TBM to the UFO/GBS payloads. The PIP is a simplex (one-way) wide-band transmission service capable of supporting high data rates. There will be three PIPs, each serving as a dedicated, primary up-link site for a specific UFO satellite. The PIP must have the ability to maximize on-orbit UFO/GBS satellite capabilities in order to extend high volume, continuous information to multiple users on various platforms over a wide range of geographical conditions and mission specific situations [Ref. 17]. These will be fixed facilities.

CINCs and CJTF/components require the ability to broadcast real-time and near real-time in-theater source information to in-theater users. This can be accomplished in two ways: virtual injection or via the transportable TIP. Virtual injection is accomplished by transmitting in-theater source information via other communications resources to the TBM element for ultimate transmission to the PIP (refer to Figure 1.2). For Phase II there will be only three TIPs.[Ref. 7:p. 11]

The Receive Terminal element will consist of a small satellite receive antenna, Low Noise Block-converter-amplifier (LNB), and a Common Demodulator/Decoder. It is to provide high speed, multimedia communications and information to forces during joint tactical operations. It will operate as a receive wide-band transmission service capable of supporting high data rates for the purpose of mission support and theater information transfer. The receive element will receive and convert the downlink signal into a bit stream which is provided to the receive broadcast management element. The RBM element will demultiplex the signal for delivery to end users. [Ref. 7:p. 11]

5. Receive Suite

The receive suite includes the receive terminal element, the receive broadcast management element and associated cryptographic equipment.[Ref. 7:p.12]

C. SATELLITE SYSTEMS

Having discussed the various elements of GBS, the following will define these elements as they would function in a bent pipe satellite communication system. A bent pipe satellite system is one where the satellite does no processing of the information. It simply acts as a relay, receiving the up-link (earth-to-space) frequency, amplifying the signal, then retransmitting the signal back to earth in the down-link (space-to-earth) frequency.[Ref. 9: p. 9] The down-link frequency must be different than the up-link to avoid self-interference. A lower frequency is usually chosen for the down-link as lower frequencies suffer lower free space loss, thus requiring lower power. The GBS payload is a bent pipe system.

1. Up-Link

a. The Up-Link : How information is Transmitted to the GBS satellite

Digital information from various sources is transmitted via terrestrial links to the TBM element. The TBM processes this information (buffers, multiplexes, formats, encrypts).

After processing, the information is transmitted as a serial bit stream from the TBM to the injection point. The presence of noise and the non-ideal nature of any communications channel introduce errors in the information being sent. Users establish an error rate or bit error rate (BER) above which the received information is not usable. Computer data normally requires a BER of at least 10^{-7}. However, for GBS, a BER of 10^{-10} or less is required. This requirement is due to the MPEG-2 video coding algorithm, which is very sensitive to errors. To achieve these low error rates, error correcting codes are incorporated into the bit stream by the encoder. (Refer to Figure 1.4) The error

correcting codes for GBS will be discussed in Chapter II. After encoding, the PIP modulates the bit stream.

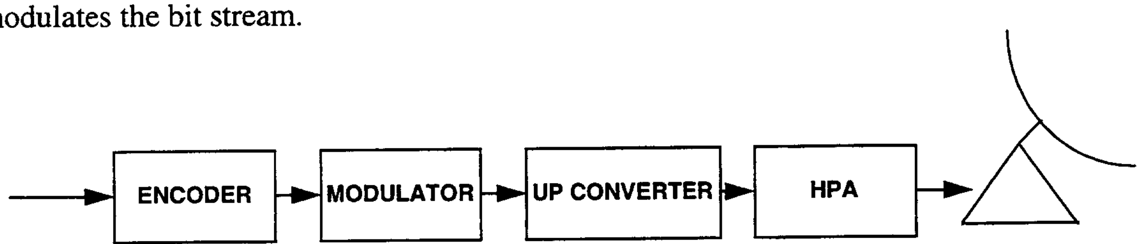

Figure 1.4: Satellite Up-Link Functional Diagram [From Ref. 9]

b. Modulation

In order to transmit baseband digital information over a satellite channel, it is necessary to transfer the digital information to a carrier wave at an appropriate frequency. This technique is called digital carrier modulation, and is performed by the modulator. [Ref. 9:p. 10] The modulator accepts the digital symbol stream from the encoder.

The most common type of digital modulation in satellite communications is called M-ary signaling, where M is the number of possible transmitted signals per symbol. With GBS, Quadriphase-Shift Keying (QPSK) is used which is a form of 4-ary signaling. A QPSK modulator accepts a serial bit stream, splits the signal via a serial to parallel converter into an in-phase channel and a quadrature channel, each at one-half the bit rate. Both are modulated with an intermediate frequency (IF) carrier (see Figure 1.5). The in-phase channel is mixed with the carrier $\cos(2\pi f_{IF}(t))$ and the quadrature channel is mixed with the carrier $\sin(2\pi f_{IF}(t))$. The two channels are then added to form the QPSK signal. The IF carrier frequency for GBS PIPs and TIPs, as for most satellite systems, is 70 MHz [Ref. 17]. An intermediate frequency rather than the actual up-link frequency is chosen to provide flexibility.

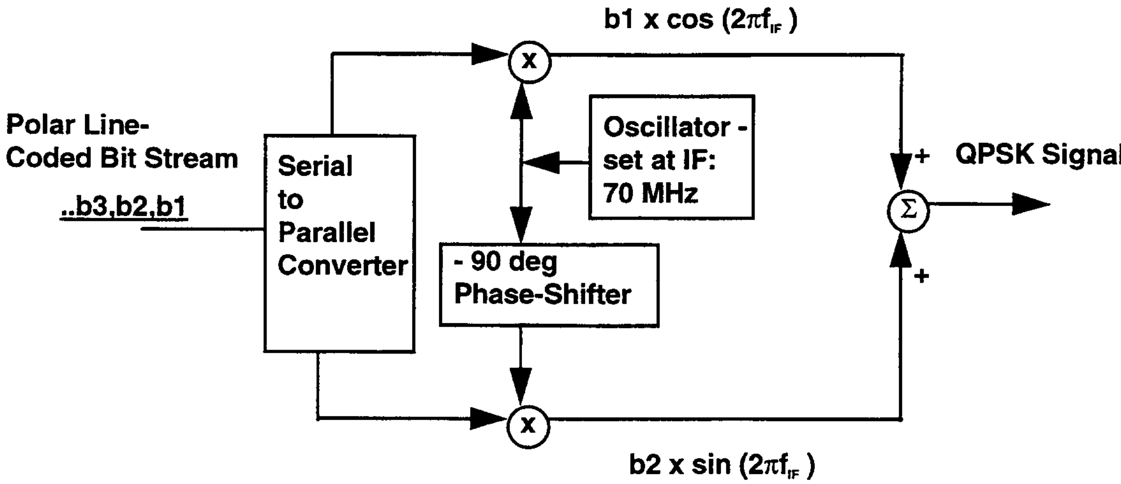

Figure 1.5: QPSK Modulator [Ref. 10]

Assuming a polar line coded signal with each bit having an amplitude of +/- 1 volt for a one or zero, respectively, the possible values for the in-phase channel are mapped as follows:

"1" => $\cos(2\pi f_{IF}(t))$

"0" => $-\cos(2\pi f_{IF}(t))$.

The possible values for the quadrature channel are mapped as follows:

"1" => $\sin(2\pi f_{IF}(t))$

"0" => $-\sin(2\pi f_{IF}(t))$.

These values are combined in the summer, and result in the following Gray encoded signal (see Figure 1.6).

"11" => $\cos(2\pi f_{IF}(t) + \pi/4)$

"01" => $\cos(2\pi f_{IF}(t) + 3\pi/4)$

"00" => $\cos(2\pi f_{IF}(t) + 5\pi/4)$

"10" => $\cos(2\pi f_{IF}(t) + 7\pi/4)$

Gray encoding is important because error is caused by noise. Noise causing a misread of the signal by a single phase will result in only a one bit error.

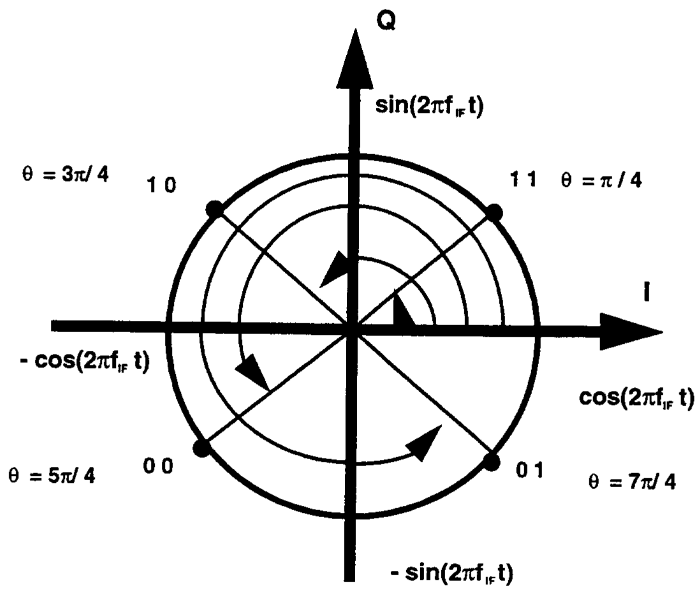

Figure 1.6: Gray encoding for a QPSK signal

c. *Up Conversion*

The upconverter (UC) accepts the modulated IF carrier from the modulator and translates its IF frequency to the up-link RF frequency. For GBS Phase II, the up-link RF frequency chosen depends upon which transponder is used. This is done by mixing the IF frequency with a local oscillator (LO) frequency. This can be accomplished with a single-conversion or with a dual-conversion process which is a cascade of two single conversions as shown conceptually in Figure 1.7. For simplicity, I will discuss only the single conversion upconverter which consists of a mixer and a bandpass filter.

Consider the coded IF carrier $\cos(2\pi\ f_{IF}(t) + (x)\pi/4)$ coming from the modulator, where x = 1, 3, 5, or 7 depending on the dibit, and the LO carrier $\cos(2\pi\ f_{LO}(t))$. The resulting mixing process yields the following product (assuming $f_{LO} > f_{IF}$): $\cos(2\pi\ f_{IF}(t) + (x)\pi/4)\cos(2\pi\ f_{LO}(t)) = 1/2\ [\ \cos(\ 2\pi\ (f_{LO}(t) - f_{IF}(t)\ ) - (x)\pi/4)\ ] + 1/2\ [\cos(2\pi\ (f_{LO}(t) + f_{IF}(t)\ ) + (x)\pi/4)\ ]$. The LO frequency is set depending upon the IF frequency of the modulator and the desired up-link frequency. In the case of GBS, the IF is 70 MHz and the desired up-link frequency is 30.095 GHz (for transponder 1). Given this the LO is set by the following formula: $f_{LO}(t) = f_{up}(t) - f_{IF}(t)$. Given our parameters,

the GBS up-link LO is set at 30.025 GHz. The amplitude of the mixed signal is 1/2 that of the original signal coming from the modulator. This is fine as the upconverted signal will pass through a high power amplifier prior to transmission to the satellite.

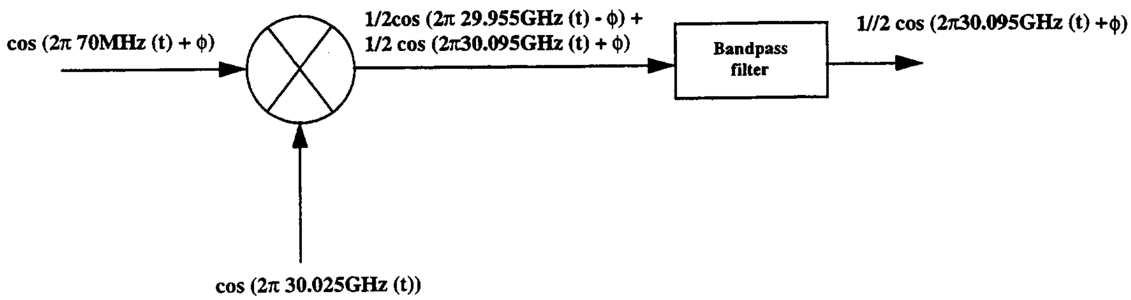

Figure 1.7: Simplified Upconverter

2. The Satellite

A bent pipe satellite is simply a relay satellite. The transponder, which accomplishes the relay, consists of a receive antenna, a low-noise-amplifier (LNA), a local oscillator, a band-pass filter (BPF), a high power amplifier (HPA), and a transmit antenna (see Figure 1.8).

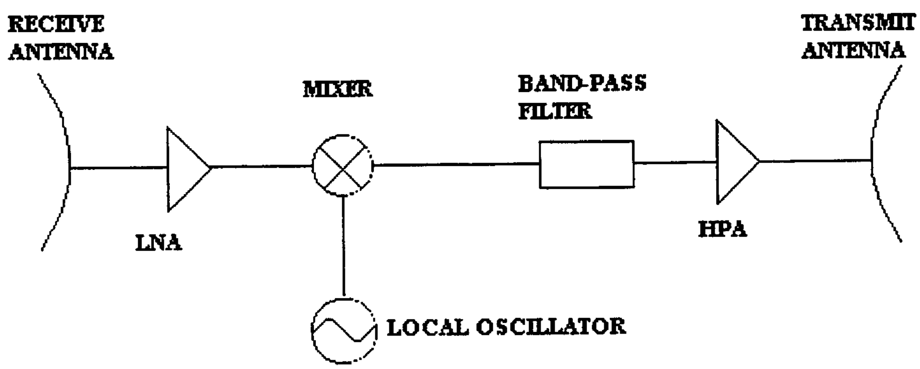

Figure 1.8: Simplified Bent-Pipe Satellite Transponder

The satellite receives the sinusoidal signal, cos(2π 30.095 GHz(t) + ϕ) (for transponder 1), from the earth station (up-link) which is highly attenuated due to free-space and other losses. This power loss is over 200dB for a geosynchronous satellite, or on the order of 10^{20}. This received signal is a current from the antenna, and this current must first be amplified by the LNA. After passing through the LNA, the signal is down-converted to a lower frequency. This is accomplished by mixing the current with a

sinusoidal current from the local oscillator. The formula for selecting the LO frequency is the same as that for the upconverter. As GBS transmits down at 20.295 GHz for transponder 1, the LO will be set at 9.8 GHz. The frequency is shifted to prevent the satellite from interfering with itself when the signal is retransmitted to earth. The reason for shifting the signal down is that lower frequencies suffer a lower free-space loss, thus requiring lower satellite power.

After mixing there are two currents. The second current term will be filtered out by the band pass filter. The bandwidth of the bandpass filters within the GBS package will be set to handle the maximum possible data rate. This is 24 Mbps. For GBS, the required bandwidth is approximately equal to the bit rate. The band pass filters will be set for 24 MHz bandwidth. Finally, the current passes through the HPA, boosting the signal power. For the UFO package, the HPA will increase the signal to 130 Watts. The power of the signal is then coupled with the gain of the transmit antenna to achieve the required EIRP for retransmission to earth. EIRP will be discussed further in the next chapter.

3. Down-Link

The down-link mirrors the up-link (see Figure 1.9). With the GBS down-link, the antenna receives the sinusoidal carrier, $\cos(2\pi\ 20.295\ \text{GHz}(t) + \phi)$ for transponder 1, and sends it to the low-noise amplifier (LNA). Again, the signal is highly attenuated from that transmitted by the satellite. The LNA amplifies the signal to an acceptable level for processing. The signal is then sent to the down converter to shift it to the receive intermediate frequency (IF). In the case of the ground receive terminal (GRT), the IF will be 950 to 2050 MHz. The GRT has a wide IF range to allow compatibility with satellites operating at other frequencies. The signal is then passed on to the demodulator.

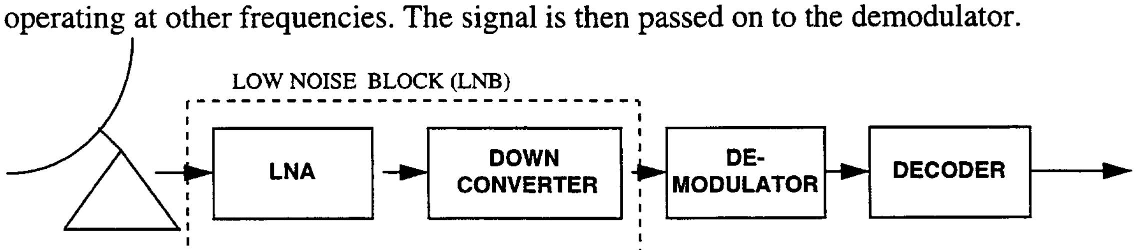

Figure 1.9: Satellite Down-Link Functional Diagram

D. SUMMARY

This chapter introduced GBS Phase II system architecture and covered its various components: space, broadcast management, terrestrial communications, terminal segment, and receive suite. These elements were put into context with function of a bent pipe communications satellite. The next chapter will discuss the expected performance of GBS Phase II, with emphasis on UFO 8 supporting theater users in the Korean AOR. It will introduce factors which adversely effect GBS performance, excluding atmospheric effects. Chapter III will be devoted to a discussion of atmospheric effects on GBS performance.

II. GBS PHASE II PERFORMANCE

A. PERFORMANCE OF SATELLITE SYSTEMS

In the simplest terms, the GBS satellite communications system is simply a method for conveying digital data, a virtual pipe for transmitting bits. So when considering GBS we are really concerned with how many bits it is able to move, its capacity and performance. GBS capacity can be looked at from several different technical criteria. First is the available bandwidth. With GBS there is 1 GHz bandwidth allocation (from 30-31 GHz up and from 20.2 -21.2 down). The number of bits per second which can be sent through 1GHz frequency spectrum depends on the modulation scheme. With QPSK modulation, the rate at which bits can be sent through a given bandwidth (B) roughly equals the bandwidth. As each GBS payload has a 1 GHz frequency allocation, it is possible that the satellite can relay 1 Gbps of data. However, this isn't the complete picture. This information must be transmitted with a minimum number of errors. As mentioned in the previous chapter the maximum error rate which GBS will be able to tolerate is 10^{-10}. Expected BER is directly related to the power of the signal and the power of noise, i.e. CNR (carrier power to noise ratio). The greater the CNR, the lower the expected BER. This chapter will discuss factors which effect the carrier to noise ratio and, in effect, limit the performance of the system.

B. FACTORS AFFECTING GBS PHASE II PERFORMANCE

1. Noise

In all transmission channels there are imperfections, primarily noise, which will distort the signal. Noise analysis of satellite communications systems is customarily based on an idealized form of noise, *white noise.* White noise is considered constant over the entire frequency range of the system and noise power per unit bandwidth (hertz) can be approximated by the equation:

$$No = kT \tag{2.1}$$

where k is Boltsmann's constant, 1.38 x 10^{-23} joules/K°, and T is the absolute ambient temperature in degrees Kelvin, usually take to be 290° K. As the power spectral density of white-noise is directly proportional to temperature, it is also referred to as thermal noise. The total available noise power in a bandwidth is approximated by

$$N = kTB \tag{2.2}$$

where B is the bandwidth of the system.

For practical communications analysis, we need to quantify noise power (N) as it enters a receiver. The available noise entering a receiver can be approximated by equation (2.2). However, T is replaced by Te, the equivalent temperature of the receiver. The equivalent temperature of a receiver is often referred to indirectly by a common system specification, Noise Figure (NF). NF relates to Te by the following equations [Ref. 9]:

$$NF = (T + Te)/\,T \tag{2.3}$$

$$Te = T\,(NF - 1) \tag{2.4}$$

where T is ambient temperature measured in degrees Kelvin. To compute the total noise in a Ground Receive Terminal (GRT) or a Ship-board Receive Terminal (SRT) the temperature of the antenna must also be taken into account to determine the total system temperature (Tsys). This relates to overall system performance as receiver quality is determined by receiver gain/receiver temperature (G/T). This value is also referred to as the figure of merit of a receiver (FOM). There are three elements to determining Tsys: the antenna temperature Ta, the noise generated due to resistance in the antenna feed and waveguide, and Te. Tsys is estimated by the following equation:

$$Tsys = Ta\,/Lw + (\,1 - 1/Lw)\,T + Te \tag{2.5}$$

where Ta will be between 150 ° K to 20 ° K for an antenna elevation angle 5° - 90°, respectively, for a 20 GHz signal [Ref. 5:p. 377], and Lw is the loss factor in the antenna

feed and waveguide and T is ambient temperature in degrees Kelvin. The total noise power in the system is

$$Nsys = k\ Tsys\ B. \tag{2.6}$$

2. Signal Power

This discussion on signal power will be limited to the satellite down-link. However, it is applicable for the up-link as well. Recall that the central issue is to deliver enough signal power relative to noise to ensure the system achieves the required BER. The GBS packages aboard UFO 8, 9, and 10 have four transponders capable of transmitting 130 watts of power, each (Pt). Gt is the gain of the transmitting antenna in the direction in which the maximum power is radiated; this is called the boresight of the antenna. It is a measure of the increase in power radiated by the antenna over that radiated from an isotropic source. Pt is amplified by the gain of the transmitted antenna, Gt, to deliver what is referred to as effective isotropic radiated power (Pt x Gt = EIRP). Isotropic power is spread out over the area of transmission, $4\pi R^2$. The signal power which reaches the receiver in the direction of the boresight is given by

$$\Omega = EIRP/4\pi R^2 \tag{2.7}$$

where Ω is the power flux density at the receiver.[Ref. 10:p. 616] The gain of the receiver is given by

$$G_R = 4\pi\ A_{eff} / \lambda^2 \tag{2.8}$$

where λ is the wavelength of the transmitted signal and A_{eff} is the effective aperture of the receiver antenna. The received power is

$$P_R = A_{eff}\,\Omega. \tag{2.9}$$

Using equations (2.7) and (2.8)

$$P_R = EIRP * G_R / (4\pi R / \lambda)^2. \tag{2.10}$$

The term $(4\pi R / \lambda)^2$ is referred to as the Free Space Path Loss (LFS) where R is the distance from the transmitter to the receiver. Equation (2.10) gives us our total signal or carrier power. As can be seen, the received power will be reduced by the square of the distance. Carrier power is the standard term for signal power in satellite communications systems. Our satellite system performance figure is quantified by a carrier to noise power ratio and is given by

$$CNR = P_R / k \, Tsys \, B. \tag{2.11}$$

The simplicity of this formula stems from the use of noise temperature as the measure of how noisy the system is. In a link budget, one normally converts these values into decibels (10 $\log_{10}$ (value (e.g. Pr, k B)) to determine

$$CNR\ (dB) =$$
$$EIRP\ (dBW) + G_R/Tsys\ (dB) - B\ (dB/Hz) - LFS(dB) - k\ (dB/J/K) \tag{2.12}$$

3. Satellite Distance and its Relationship to Signal Power and Antenna Elevation Angle

The importance of satellite distance to the performance of a communications system has been discussed. It affects the LFS and it also determines the antenna elevation angle. The importance of satellite elevation angle relates to how much of the path is in the atmosphere. This will be discussed in the next chapter. This subsection will discuss how antenna elevation angle can be determined, and with that information, how the distance from the ground station to the satellite can be determined. First, the simple case of a geostationary satellite will be considered. A geostationary satellite is one whose nadir remains fixed. It has an orbital period of one sidereal day (23 hr 56 min 4 sec) and zero inclination. Next to be considered is the slightly more complex case of a geosynchronous orbit, where the orbital period is still one sidereal day, but the satellite has some orbital inclination.

a. Satellite Distance And Antenna Elevation Angle for a Geostationary Satellite

To determine the antenna elevation angle, E, at the ground station consider the triangle SGC in Figure 2.1. By determining the angle between the vector **CS** and **CG**, γ (see figure 2.2), it is straight forward to determine the antenna elevation angle. To determine the angle γ, determine the angle between the vector **CM** and **CG** which is the station latitude (θ_l) if M is at the equator, and the angle between the vectors **CS** and **CM** which is the difference in the longitude of the satellite and the longitude of the ground station $|\theta_{LS} - \theta_{LG}|$. By the definition of the dot product we know that

$$\mathbf{CG} \bullet \mathbf{CS} = |\mathbf{CG}| \; |\mathbf{CS}| \cos\gamma \tag{2.13}$$

These vectors have the following components:

$$\mathbf{CG} = |\mathbf{CG}| \; (0_{x1} \qquad\qquad + \cos\theta_{l\;x2} \qquad\qquad + \sin\theta_{l\;x3})$$
$$\mathbf{CS} = |\mathbf{CS}| \; (\sin|\theta_{LS} - \theta_{LG}|_{x1} + \cos|\theta_{LS} - \theta_{LG}|_{x2} + 0_{x3}).$$

Therefore

$$\mathbf{CG} \bullet \mathbf{CS} = |\mathbf{CG}| \; |\mathbf{CS}| \; (\cos\theta_l \cos|\theta_{LS} - \theta_{LG}|).$$

After some substitution we find that

$$\gamma = \cos^{-1} (\cos\theta_l \cos|\theta_{LS} - \theta_{LG}|). \tag{2.14}$$

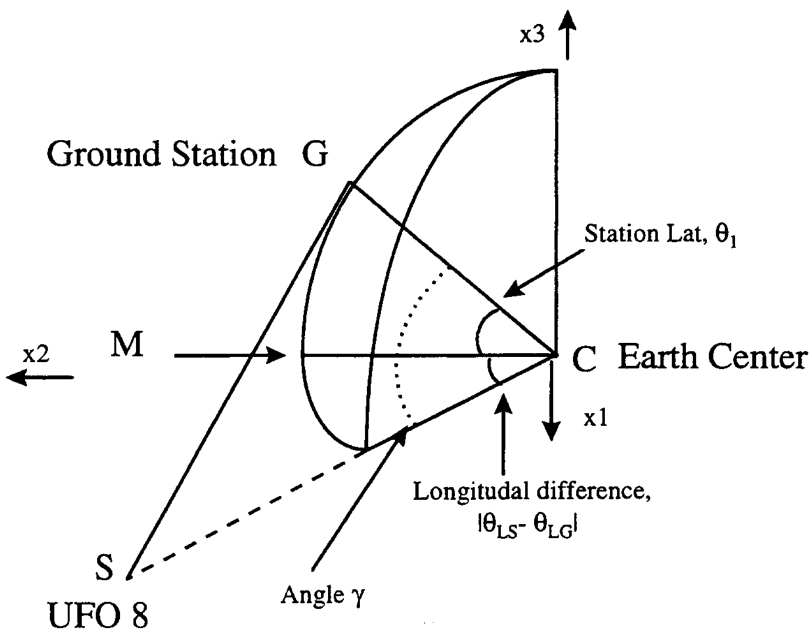

Figure 2.1: Satellite to Ground Station Geometry.

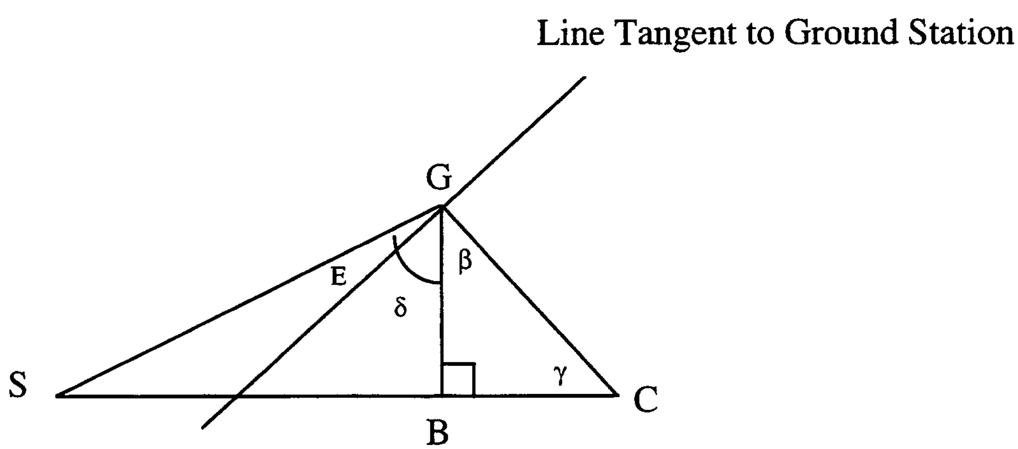

Figure 2.2: Triangle to Calculate Antenna Elevation

The ground station elevation angle can be determined by the following relationships;

$$E = \beta + \delta - 90$$
$$E = (90 - \gamma) + \delta - 90$$
$$E = \delta - \gamma, \quad (2.15)$$

as E is the sum of the angles $\beta + \delta$ minus the angle formed by the line tangent to the ground station, which is 90 degrees. We have shown how γ is derived. The formula for δ is as follows,

$$\delta = \tan^{-1} [(r - Re \cos \gamma) / Re \sin \gamma] \tag{2.16}$$

where r is the semi-major axis of a geosynchronous satellite, 42,164.2 km, Re is the radius of the earth 6378 km, Re cos γ is the distance **CB** (Figure 2.2), r - Re cos γ is the distance **BS** (Figure 2.2), and Re sin γ is the distance **GB**. Using the law of cosines, we determine the distance from the satellite to the ground station, d (**SG** in figure 2.2)

$$d^2 = r^2 + Re^2 - 2\, Re\, r\ \sin [E + \sin^{-1} ((Re / r) \cos E)] \quad . \tag{2.17}$$

Or, the distance can be found using the angle γ from

$$d^2 = r^2 + Re^2 - 2\, Re\, r\ \cos \gamma. \tag{2.18}$$

b. Satellite Distance and Antenna Elevation Angle for a Satellite with an Inclined Orbit

UFO 8 will have an orbital inclination of 6 degrees. So the satellite's nadir will drift periodically in a figure 8 pattern centered at its ascending node (see Figure 2.3). The drift will be maximized at 6 and 18 hours after crossing the ascending node. The amount of drift can be computed by the formulas in Table 2.1.

Hours	Y/Re	Z/Re
0	0	0
3	(-1/2) (1-cos i)	$(1/2)^{.5}$ (sin i)
6	0	(sin i)
9	(-1/2) (1-cos i)	$(1/2)^{.5}$ (sin i)
12	0	0
15	(1/2) (1-cos i)	$(-1)(1/2)^{.5}$ (sin i)
18	0	(-1)(sin i)
21	(-1/2) (1-cos i)	$(-1)(1/2)^{.5}$ (sin i)
24	0	0

Table 2.1: geosynchronous Nadir for given time after crossing ascending node.

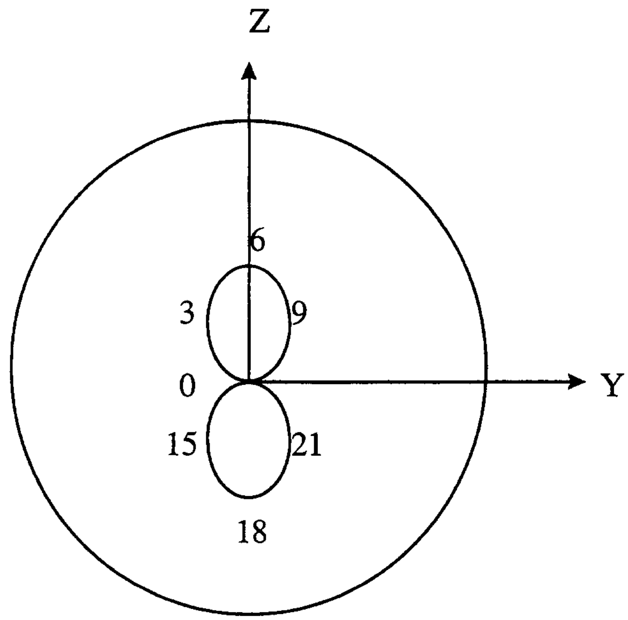

Figure 2.3: Geosynchronous Nadir Drift.

The formula for the length and width of each lobe can be take from Table 2.1.

$$Z\,(6hr) - Z\,(0hr) = Re \sin 6 = 666 \text{ nm.} \tag{2.19}$$

$$Y(9hr) - Y(3hr) = Re\,(1 - \cos 6) = 35 \text{ nm.} \tag{2.20}$$

The maximum change in latitude and longitude from nadir can be derived as follows:

$$\Delta lat = \sin^{-1}(Z(6hr)/Re) = 6 \text{ degrees} \tag{2.21}$$

$$\Delta lon = \sin^{-1}(Y(9hr)/Re) = .31 \text{ degrees} \tag{2.22}$$

Equation (2.14) can be modified to account for the additional difference in satellite longitude and latitude. For simplicity, only the worst case and best case will be considered, i.e. when the satellite is at its peak lobes, hour 6 and 18. If the satellite is at its peak lobe and the earth station is in the northern hemisphere, the best case is at hour 6 after crossing the ascending node. Simply subtract the satellite latitude from the ground station latitude. The worst case for a satellite in the northern hemisphere is when the satellite is at hour 18. Add the satellite latitude to the ground station latitude.

$$\gamma = \cos^{-1} (\cos |\theta_{IG} \pm \theta_{IS}| \cos |\theta_{LS} - \theta_{LG}|.) \qquad \text{(2.14 modified)}$$

Using this modified equation, insert the value for γ into equations (2.15), (2.16) and (2.18) shown below to determine the adjusted elevation angle E and distance. To best predict LFS for GBS, system managers should use the worst case distance in equation (2.10).

$$E = \delta - \gamma$$
$$\delta = \tan^{-1} (r - Re \cos \gamma / Re \sin \gamma)$$
$$d^2 = r^2 + Re^2 - 2 \, Re \, r \cos \gamma$$

As modified equation (2.14) was empirically derived, it is important to determine how accurate it is. It assumes a perfectly spherical earth, i.e. the radius of the earth being constant for all latitudes and longitudes. This is not the case. A very precise orbital prediction tool, Analytical Graphics' Satellite Tool Kit (STK), was used to compute the distances to UFO 8 (172 E) from a location in Korea (36 N - 129 E), and a location in the south Pacific (a notional battle group) (24 S - 147 W) and compared against values derived from equation (2.18). The distances derived are for 0, 3, 6, 9, 12, 15, 18, 21 and 24 hours after nadir measured in km.

time after nadir	Equation 2.18	STK derived	% difference
0	38733	38727	0.01
3	38521	38427	0.24
6	38442	38342	0.31
9	38524	38451	0.19
12	38733	38731	0.01
15	38963	39030	0.17
18	39066	39272	0.26
21	38965	39043	0.19
24	38733	38720	0.03

Table 2.2: Empirically derived distances and STK derived distances from UFO 8 to Korea (36 N - 129 E).

time after nadir	Equation 2.18	STK derived	% difference
0	38048	38044	0.01
3	38222	38279	0.15
6	38300	38367	0.17
9	38220	38254	0.08
12	38048	38041	0.02
15	37902	37855	0.12
18	37847	37770	0.21
21	37899	37836	0.16
24	38048	38048	0.00

Table 2.3: Empirically derived distances and STK derived distances from UFO 8 to notional Battle Group in the south Pacific (24 S - 147 W).

The difference between the distances derived from equation (2.18) using the modified equation (2.14) and the distances derived from STK can be attributed to the fact that STK accounts for the earth's equatorial bulge, effects of the moon's gravitation, and other anomalies. As these differences are very slight, it can be assumed that the simple spherical math equations sufficient for link analysis. Tables 2.4 and 2.5 show the difference between the elevation angles derived from equation (2.15) and the elevation angles derived from STK.

time after nadir	Equation 2.15	STK derived	difference
0	28.65	28.70	0.05
3	31.02	32.10	1.08
6	31.93	33.30	1.37
9	30.99	31.83	0.84
12	28.65	28.67	0.02
15	26.15	25.43	0.72
18	25.05	23.94	1.11
21	26.13	25.29	0.84
24	28.65	28.79	0.14

Table 2.4: Empirically derived elevation angles and STK derived elevation angles for UFO 8 to Korea (36 N - 129 E).

time after nadir	Equation 2.15	STK derived	difference
0	36.62	36.66	0.04
3	34.51	33.83	0.68
6	33.58	32.79	0.79
9	34.53	34.12	0.41
12	36.62	36.70	0.08
15	38.44	39.04	0.60
18	39.14	40.14	1.00
21	38.47	39.28	0.81
24	36.62	36.62	0.00

Table 2.5: Empirically derived elevation angles and STK derived elevation angles for UFO 8 to notional Battle Group in the south Pacific (24 S - 147 W).

Figures 2.4 and 2.5 show UFO 8's position at 6 and 18 hours after Nadir, respectively. Notice the change in the access and coverage area.

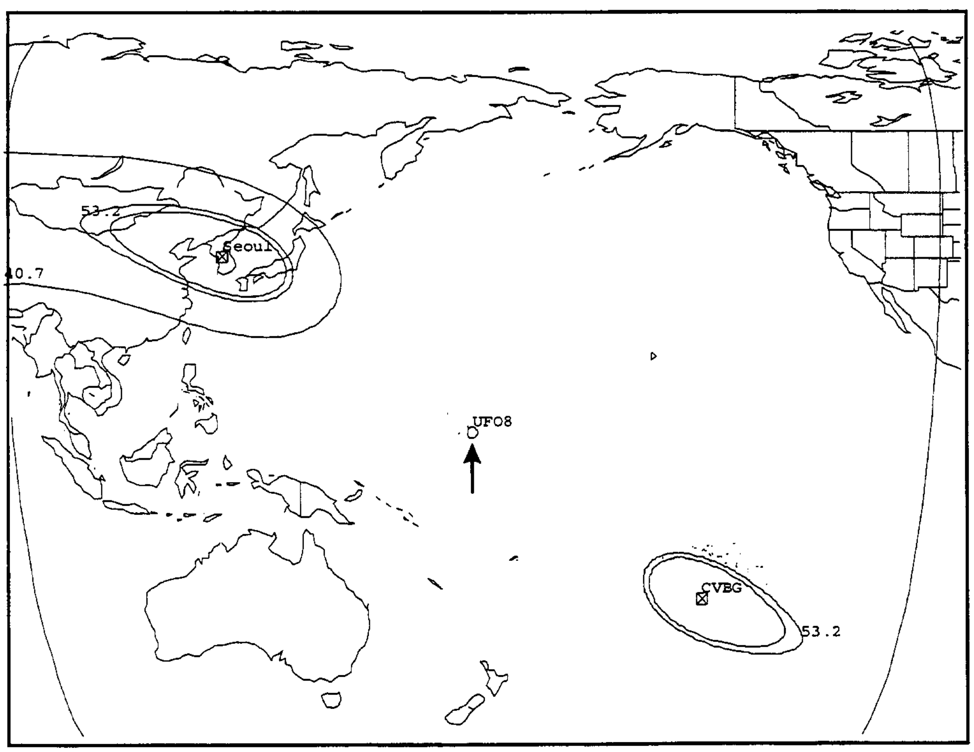

Figure 2.4: UFO 8 6 hours after crossing nadir: UFO 8's northern most point.

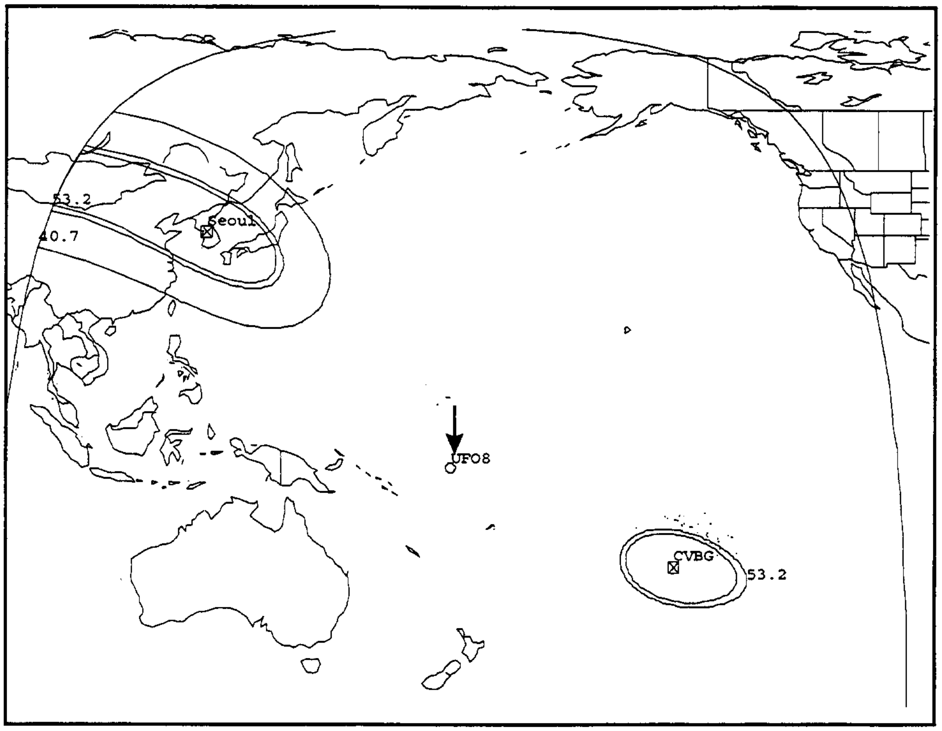

Figure 2.5: UFO 8 18 hours after crossing nadir: UFO 8's southern most point.

4. Energy Per Bit

As GBS is transmitting digital information, BER performance is determined by the ratio of energy per bit (E_b) to noise power per unit bandwidth (i.e. hertz) (N_0): E_b/N_0. Recall from our previous discussion No is N / B or kTsys. E_b is the carrier power divided by the number of bits per second. In digital communications systems there must be sufficient E_b/N_0 to maintain the required bit error rate (BER). The BER for GBS must not exceed 10^{-10}. The link budget for deriving E_b/N_0 is

$$E_b/N_0\ (\text{dB}) = \text{EIRP (dBW)} + G_R/\text{Tsys (dB)} - 10\log_{10}(\text{bit rate})\ (\text{dB/bps}) - \text{LFS (dB)} - k\ (\text{dB/J/K}) \qquad (2.23)$$

This link budget neglects other losses such as polarization and antenna pointing error losses. The signal can develop polarization errors due to atmospheric phenomena such as rain and other gaseous absorption. It is impractical to assume that the transmit antenna can be pointed exactly at the receive antenna at all times. So we must account for

the expected antenna pointing error. Other losses which must be taken into account are signal attenuation due to rain and atmospheric absorption. These will be covered in chapter III.

5. Bit Error Rate (BER)

For GBS to meet its required BER, it must have sufficient E_b/N_0. For a QPSK modulated signal, the required E_b/N_0 to meet a BER of 10^{-10} or less is 13 dB or more (refer to Figure 2.6) [Ref. 19]. Error correction coding helps mitigate errors and reduces the required E_b/N_0 for a given BER requirement. Most digital communication systems employ some form of error correction. GBS uses two forms of forward error correction coding (FEC): a convolutional code with a Viterbi decoder concatenated with a Reed-Solomon block code. FEC is a method of error control that employs the adding of systematic redundancy at the transmit end of a link such that errors caused in the channel can be corrected at the receiver by means of a decoding algorithm. Convolutional codes are useful in correcting errors caused by a weak signal. Reed-Solomon is optimized for correcting errors caused by burst noise. Burst noise is caused by natural phenomena such as lightning and by physical events such as radar pulses or antenna vibration With the combination of the 1/2 rate convolutional code and Reed-Solomon, GBS requires an E_b/N_0 of just over 6 dB according to Figure 2.6 [Ref. 19]. However, according to the European Telecommunications Standards Institute, the requirement is only 4.5 [Ref. 3]. The difference between the E_b/N_0 required without error correction and the E_b/N_0 required with error correction is called coding gain. With our combination of FEC and Reed-Solomon we get a coding gain of 7 dB according to the more conservative estimate. As can be seen from Figure 2.6, if the E_b/N_0 for GBS falls below 6 dB, the BER jumps considerably. If the GBS E_b/N_0 falls to 5 dB (loses just 1 dB of signal strength below requirement), the BER jumps to 10^{-6}. GBS's performance as a communications channel is not limited by bandwidth. It is power limited, i.e. limited by the required E_b/N_0.

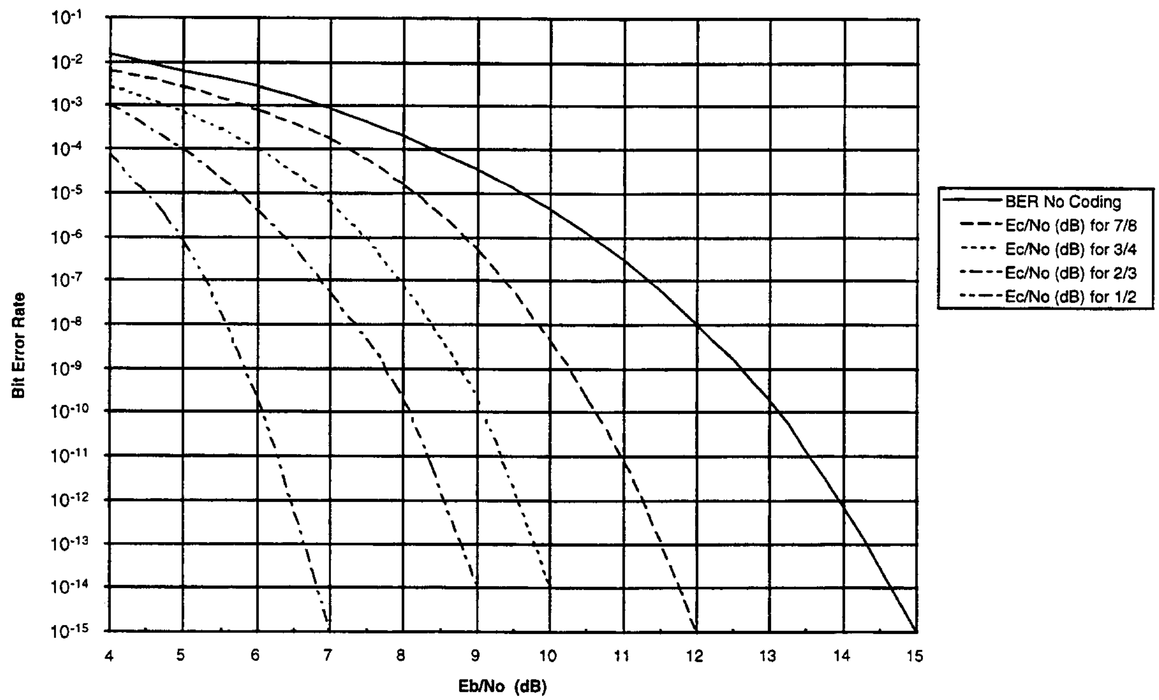

Figure 2.6: Bit error probability vs. Eb/No with convolutional inner coding and Reed-Solomon outer coding [From Ref. 19].

C. GBS PERFORMANCE

A link-budget is the method used to quantify satellite link performance in an easily understood format. Most published link-budgets for GBS use the following frequencies: 30.5 GHz up and 20.7 GHz down. The free space path loss assumes a 10 degree elevation angle with a corresponding distance from ground station to satellite of 40,598 km. As previously stated, for GBS, with QPSK modulation, 1/2 rate convolutional coding, and Reed-Solomon block coding, the minimum E_b/N_0 for the required BER of 10^{-10} is 6 dB. However, published GBS link-budgets use a more conservative minimum E_b/N_0 of 6.5 dB. Table 2.6 shows the link-budgets published in the Space Segment Specification for Interim Global Broadcast Service for the three GBS coverage beams: 24Mbps PIP injected spot beam (transponder 1 and 2), the TIP injected 6 Mbps spot beam (transponder 3), and the PIP injected T1 (1.544 Mbps) wide area beam (transponder 4).

24 Mbps Spot Beam

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.30	dB
Rain Loss	0.00	dB
Atmoshperic Loss	0.00	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	95.85	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.90	dB
Rain Loss	0.00	dB
Atmospheric Loss	0.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	16.00	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	86.37	sB-Hz
C/N0 Total	85.91	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	12.18	dB
Required Eb/N0	6.50	dB
Margin	5.68	dB

6 Mbps Theater Injected

UPLINK		
EIRP	78.00	dBW
Free Space Loss	214.30	dB
Rain Loss	0.00	dB
Atmospheric Loss	0.00	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	93.85	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.90	dB
Rain Loss	0.00	dB
Atmoshperic Loss	0.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	16.00	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	86.37	sB-Hz
C/N0 Total	85.66	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	17.75	dB
Required Eb/N0	6.50	dB
Margin	11.25	dB

1.544 Mbps Area Beam

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.30	dB
Rain Loss	0.00	dB
Atmospheric Loss	0.00	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	95.85	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.90	dB
Rain Loss	0.00	dB
Atmoshperic Loss	0.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	16.00	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	73.87	sB-Hz
C/N0 Total	73.84	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	11.96	dB
Required Eb/N0	6.50	dB
Margin	5.46	dB

Table 2.6: GBS Link Budgets

All values entered into a link-budget are in decibels to facilitate addition. Refer to equations 2.16 and 2.17 for the details of these link budgets. On the up-link, the PIP is providing an EIRP of 84 dBW. As free space loss is a function of distance and frequency, the higher the frequency and longer the path the higher the free space loss. You will notice that because the up-link frequency is higher that the down-link frequency, 30 GHz versus 20 GHz, respectively, there is lower free space loss in the down-link. The receiver G/T assumes a 22 inch reflector with an efficiency of .6 and a receiver with a 1.4 dB noise figure. The final entry for the up-link is the carrier to noise ratio (C/N_0). On the down-link, the satellite will deliver 53.2 dBW at the edge of the 500 nm beam for the 24 Mbps spot beam. Once the up-link and down-link C/N_0 are derived, we must compute total C/N_0. C/N_0 total is given by:

$$C/N_0 \text{ total} = 1 / (1/ C/N_0 \text{ (up)} + 1/ C/N_0 \text{ (down)}). \text{ (values not in dB).} \qquad (2.24)$$

The final entry in these link-budgets is the margin. This is the difference between the achieved E_b/N_0 and required E_b/N_0. This means that for the 24 Mbps spot beam, the

signal can loose a total of 5.68 dB before the BER begins to climb. A margin of at least 2 dB is highly desirable to accommodate hardware variations.

Having looked at the general link budget presented in the Space Segment Specification, now consider a more realistic link budget (Table 2.7) taking into account the actual frequencies of each of the transponders and the orbital inclination of UFO 8. For this link budget consider a ground station located in Korea, 36 N 129E, and a PIP located at Camp Roberts, just south of NPS. At the ground station assume there is a TIP and a GRT. The distance from the ground station to the satellite will vary from 38,442 km to 39,066 km, the elevation angle of the antenna will vary from 31.9 degrees to 25.045 degrees, respectively. The distance from the PIP to the satellite will vary from 40,453 km to 40,771 km the elevation angle of the antenna will vary from 11.24 degrees to 8.27 degrees, respectively. The free space path loss will vary as well.

As stated in Chapter I, there will be four data streams in the four transponders on the GBS package. The actual frequencies (in GHz) for GBS are as follows:

Transponder 1 (24 Mbps): 30.095 (up-link) - 20.295 (down-link)
Transponder 2 (24 Mbps): 30.215 (up-link) - 20.415 (down-link)
Transponder 3 (6 Mbps): 30.275 (up-link) - 20.475 (down-link)
Transponder 4 (1.544 Mbps): 30.395 (up-link) - 20.595 (down-link)

where transponder 1 and 2 will be transmitted by the same antenna into a spot beam, transponder 3 is reserved for the theater up-link and will be transmitted by a second antenna into a spot beam, and transponder 4 can either be transmitted through the second transmit antenna along with the channel 3 broadcast or transmitted via a third antenna for a nominally 2000nm area beam. (refer to Figure 1.3) In the link-budget presented, transponder 4 is assumed to be transmitted via the third antenna. For the 24 Mbps spot beam link budget, the frequencies for transponder 2 are used.

These link budgets assume a worst case distances: 40,771 km from the PIP to UFO 8 and, 39,066 km from TIP and GRT to UFO 8. The worst case antenna elevation angle for the PIP is 8.27 degrees and the antenna elevation angle for the TIP and GRT are both 25.045. As can be seen from Table 2.7, margins for these link budgets are fairly good. However, these link budgets do not account for atmospheric losses. The variation in LFS isn't significant. However, the variation in antenna elevation is significant. A 5 degree variation in elevation angle will cause a significant variation in the amount of the

satellite path which is in the atmosphere. The amount of the satellite link within the atmosphere will cause considerable variation in atmospheric losses.

24 Mbps Spot Beam

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.22	dB
Rain Loss	0.00	dB
Atmoshperic Loss	0.00	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	95.93	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.43	dB
Rain Loss	0.00	dB
Atmospheric Loss	0.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	16.00	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	86.84	sB-Hz
C/N0 Total	86.34	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	12.61	dB
Required Eb/N0	6.50	dB
Margin	6.11	dB

6 Mbps Theater Injected

UPLINK		
EIRP	78.00	dBW
Free Space Loss	213.91	dB
Rain Loss	0.00	dB
Atmospheric Loss	0.00	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	94.24	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.51	dB
Rain Loss	0.00	dB
Atmoshperic Loss	0.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	16.00	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	86.76	sB-Hz
C/N0 Total	86.05	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	18.14	dB
Required Eb/N0	6.50	dB
Margin	11.64	dB

1.544 Mbps Area Beam

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.31	dB
Rain Loss	0.00	dB
Atmospheric Loss	0.00	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	95.84	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.56	dB
Rain Loss	0.00	dB
Atmoshperic Loss	0.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	16.00	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	74.21	sB-Hz
C/N0 Total	74.18	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	12.29	dB
Required Eb/N0	6.50	dB
Margin	5.79	dB

Table 2.7: UFO 8 Link Budgets for the Korean theater; transponders 2-4.

As will be seen in Chapter III, when atmospheric losses are considered, the link closure for GBS is very tenuous. Because of this, it will be clear that Phase II must incorporate an ability to vary the data rate to ensure maximum link availability.

D. SUMMARY

This chapter has analyzed non-environmental factors which will limit the performance of GBS Phase II. We have shown how the inclination of the UFO satellites will cause the distance from the satellite to the ground station and the corresponding antenna elevation angle to vary over a 24 hour period. We have developed a realistic link budget for UFO 8 to the Korean theater using the actual transponder frequencies. The next chapter will discuss environmental losses which will impact GBS Phase II performance. Chapter IV will then incorporate expected environmental losses into our UFO 8 link budget.

III. ATMOSPHERIC LOSSES

A. INTRODUCTION

Without considering atmospheric losses, GBS has margins ranging from 5.79 dB for the T1 area beam to 10.87 for the theater up-link. However once atmospherics are accounted for, these margins will diminish. As mentioned in Chapter I, the optimum radio-frequency band for a robust satellite link is between 1 and 10 GHz. This frequency band is termed the "noise window," as this is where galactic and man-made noise are at a minimum.[Ref. 5] Furthermore, attenuation due to precipitation and atmospheric absorption can generally be neglected in this frequency range. To avoid the problem of frequency congestion, DoD has elected to use a frequency band considerably higher than the noise window for GBS: 20-21 GHz (K-band) for the satellite down-link and 30-31 GHz (Ka-band) for the up-link. The K/Ka bands offer three advantages: larger band width allocation (GBS has a 1 GHz BW allocation), smaller probability of interference and smaller equipment size. However, this RF range is more susceptible to atmospheric impairments, especially rain, than are lower frequency ranges.

B. PROPAGATION DIFFICULTIES ABOVE 18 GHZ

When considering radio waves above 18 GHz propagating through the atmosphere, we must consider more than just LFS. Oxygen and water vapor in the atmosphere will absorb a portion of the signal. However, attenuation due to precipitation is the major concern. Precipitation attenuation above 18 GHz can easily exceed that of all other sources of attenuation in the atmosphere. To illustrate the point, consider the issue of attenuation due to water vapor absorption. Even at 22 GHz, where water vapor absorption is near a peak, the RF signal attenuates only at a rate of 0.165 dB/km. So for a satellite link having 15 km of its slant path within the atmosphere (i.e. below the 0^{o}C isotherm layer), the attenuation due to water vapor absorption is only 2.47 dB. For that same satellite link, one half inch per hour of rain fall (12.7 mm/hr) will attenuate that same signal by 19.7 dB. Before discussing rain attenuation, I will briefly treat total loss of the signal due to absorption by water vapor and oxygen.

C. GASEOUS ABSORPTION

Attenuation due to water and oxygen are treated together as gaseous absorption. Gaseous absorption due to water peaks at 22.235 GHz, and peaks due to oxygen near 60 GHz. Plots for attenuation in dB/Km for oxygen and water vapor are presented in Figure 3.1 for air an temperature of 15 degrees C and a relative humidity of 7.5 g/m3. Oxygen attenuation is fairly constant relative to temperature and humidity, generally varying only with frequency. However, water vapor attenuation will vary with humidity. The published atmospheric loss for GBS assumes a 10 g/m3 humidity, for a total of 1.7dB loss for the up-link and a 2.8 dB loss for the down-link [Ref. 22]. However, in much of the Pacific Rim, humidity in the summer will usually exceed 20 g/m3. This will cause gaseous loss for the up and down link to reach 3.14dB and 5.14 dB, respectively for a 10 degree elevation angle.

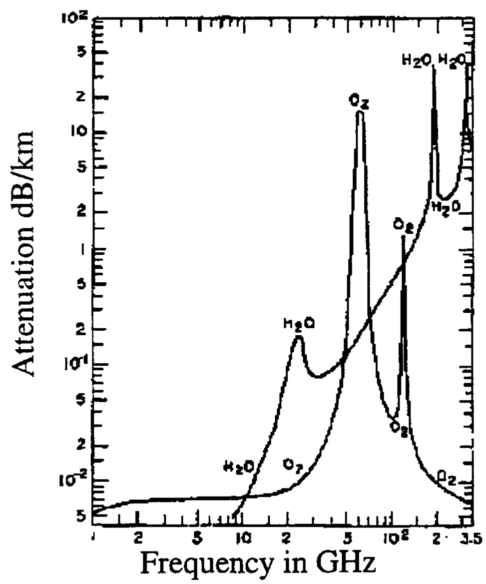

Figure 3.1: Attenuation for atmospheric gases for 15 degrees C and 7.5 g/m3 humidity [From Ref. 5]

D. RAIN ATTENUATION

1. Reflectivity of a Raindrop

Rain attenuates RF signal power by scattering it. The magnitude of signal attenuation is a function of the reflectivity or radar cross section (RCS) of a raindrop. The

reflective cross section of a raindrop is very similar to what could be expected by a sphere, as rain drops are approximately spheroids.[Ref. 20] The radius of a typical rain drop is approximately 0.75 mm [Ref. 5]. As can be determined from Figure 3.2, below 18 GHz, the reflectivity of a rain drop is rather low. In the Rayleigh region, the RCS increases as λ^{-4} until $2 \pi a / \lambda = 1$. This is illustrated in Figure 3.2. At the maximum, the reflective cross section of a raindrop measured in radar cross section normalized to πa^2, reaches around $4 \pi a^2$.[Ref. 20] After this point the reflectivity enters a resonance zone and is best approximated by Mie scattering. [Ref. 5] In this resonance zone, its reflectivity oscillates with frequency. When the radius of the raindrop is greater than 2λ, the reflectivity enters the optical region and is equal to πa^2.[Ref. 18] This is illustrated by Figure 3.2. For a 0.75 mm raindrop one would expect it to reach its maximum RCS when $\lambda = 5 \times 10^{-3}$ meters or at 60 GHz. However, due to the wide distribution of raindrop diameters and other physical phenomena, the reflectivity of rain actually peaks at 40 GHz (see Figure 3.3).[Ref. 5]

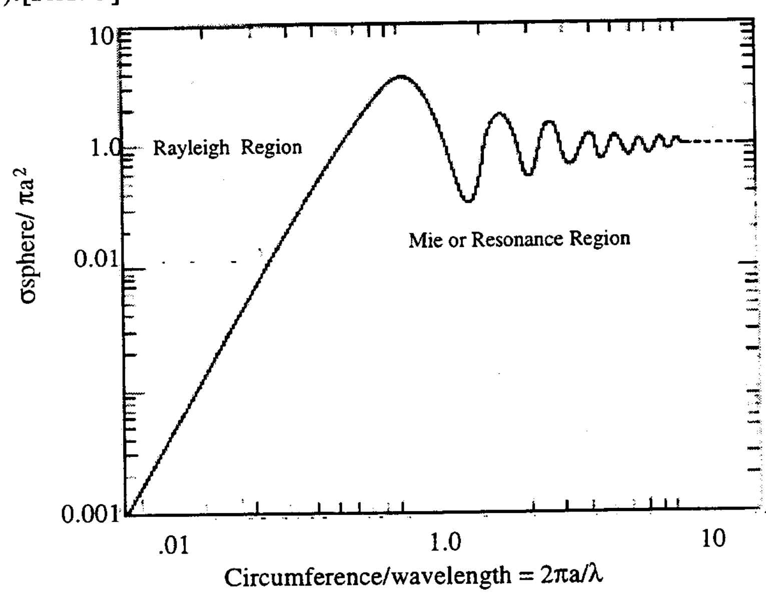

Figure 3.2: Reflectivity Cross Section of a Sphere [From Ref. 20]

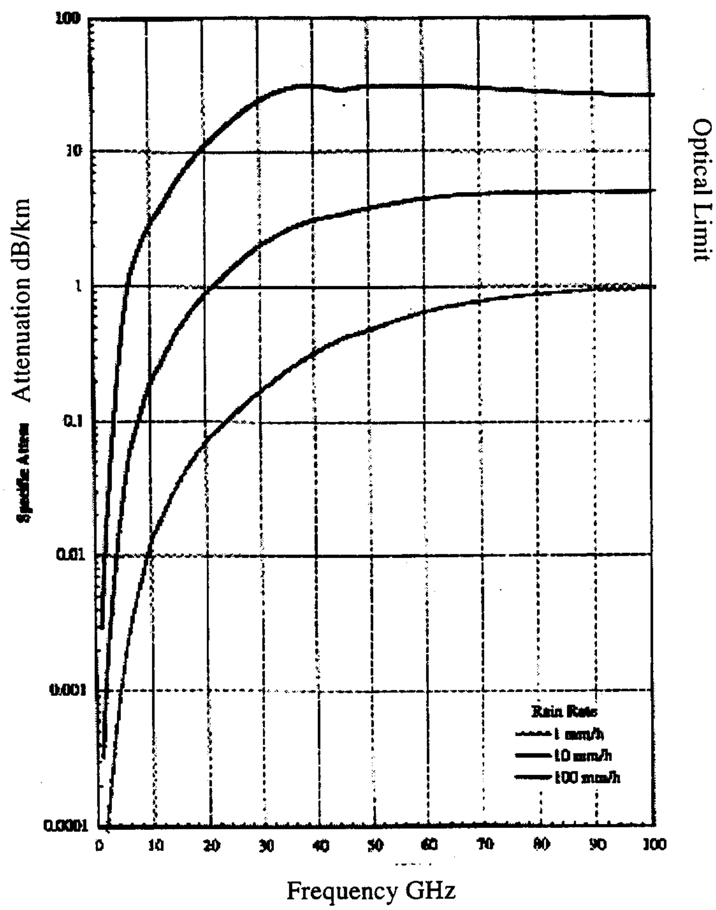

Figure 3.3: Specific attenuation caused by rain [From Ref. 2]

2. Rainfall Reflectivity

For practical rain attenuation approximation, we are not concerned with the reflectivity of a single drop but the overall reflectivity of a volume of raindrops along the propagation path. This reflectivity is measured in rainfall intensity or rain-rate, given in mm/hr. As we are concerned with frequencies below 40 GHz, we can approximate the reflectivity rain per unit volume by:

$$Ze = (\pi^5 \mid K\mid^2)/\lambda^4 \qquad (3.1)$$

where $\mid K\mid^2$ is $(\varepsilon - 1)/(\varepsilon + 2)$ and ε is the dielected constant of the scattering particles. At 10°C and a 10cm λ, $\mid K\mid^2$ is taken to be 0.93. [Ref. 18:p. 500] However, this accounts

only for the RF energy reflected directly back at the transmitter. Rain actually scatters energy in all directions. From experimental measurements, a relationship has been empirically derived between signal attenuation A (dB/km) and rainfall rate R. A is often referred to as specific attenuation. This relation is

$$A = a(R)^{b} \tag{3.2}$$

where a and b are empirically determined constants. These constants vary with frequency and have been approximated by the following equations:

$$\begin{aligned}
a &= 4.21 \times 10^{-5} F^{2.42} && 2.9 \leq F \leq 54 \text{ GHz} \\
a &= 4.09 \times 10^{-2} F^{.0699} && 54 \leq F \leq 180 \text{ GHz} \\
b &= 1.41\, F^{-0.0779} && 8.5 \leq F \leq 25 \text{ GHz} \\
b &= 2.63\, F^{-0.272} && 25 \leq F \leq 164 \text{ GHz}
\end{aligned} \tag{3.3}$$

where F is frequency in GHz [Ref. 9:p. 159]. Some values for a, b and A are given in table 3.1. The rain rate used to derive the attenuation was 1.8 mm/hr. A plot of this attenuation for 1.8 mm/hr versus frequency is given in Figure 3.4.

Freq (GHz)	a	b	A
10	0.011	1.17	0.0221
15	0.029	1.14	0.0577
20	0.059	1.11	0.1142
25	0.101	1.09	0.1936
30	0.158	1.04	0.2918
35	0.229	0.99	0.4132
40	0.317	0.96	0.559

Table 3.1: Rain rate attenuation at 1.8 mm/hr

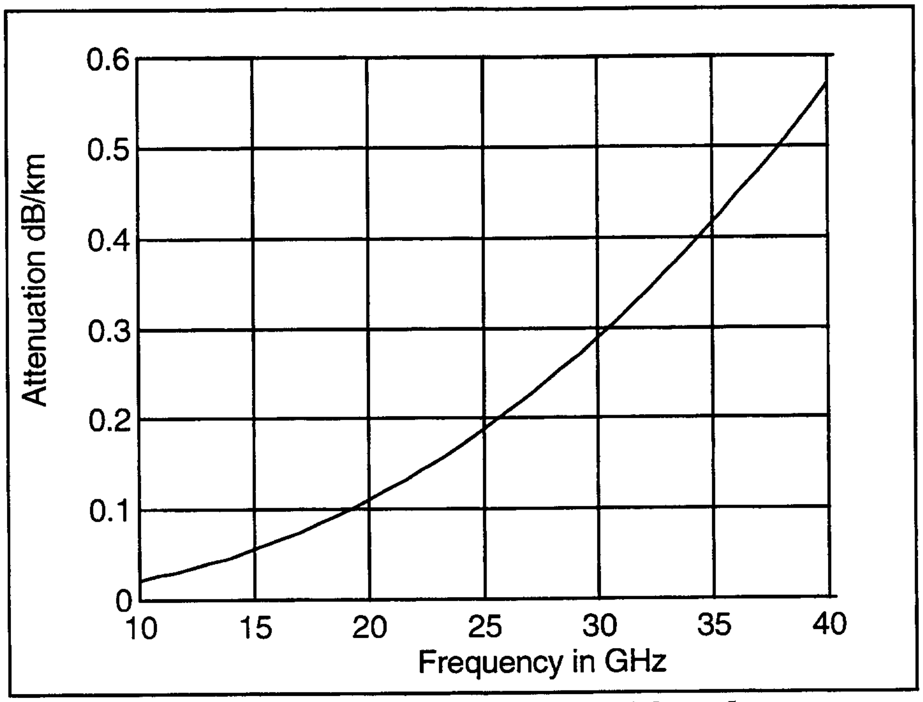

Figure 3.4: Rain rate attenuation at 1.8 mm/hr

A 20 GHz, the RF signal attenuates at a rate of 0.119 dB/km for a rainfall rate of 1.8 mm/hr. One might assume that with this empirically derived function one multiply A by the path length to obtain the total attenuation on the link. However, this assumes that rainfall rate is uniform along the signal path. According to Professor Warren Stutzman of Virginia Tech, who developed the Simple Attenuation Model (SAM), this relation holds true only for light rain.[Ref. 4] This is because light rain tends to have a rather uniform rainfall rate and is wide-spread in nature. However, with heavier rain, rainfall rates can vary widely along the path. The size of cells of heavy rain tend to be rather small, on the order of 6 km in width, but are usually surrounded by larger areas of light rain. It is possible that the RF path could traverse more than one cell of heavy rain. For accurate estimation of real-time rain attenuation, the size and orientation of a rain cells relative to the path must be known as well as the average rainfall rate along the entire path.

E. RAINFALL ALONG A SATELLITE PATH

Parameters which effect rainfall attenuation along an RF satellite path (slant path) are the height of the 0°C isotherm layer, the antenna's elevation angle, the rainfall rate, and the frequency of the signal. The first two parameters determine how much of the

satellite link is within the atmosphere and below the freezing level. The height of the 0°C isotherm layer varies with latitude and season. Above this layer, usually only frozen precipitation is found. Frozen precipitation has a negligible effect on radio frequency (RF) propagation. However, during intense rain, there are often updraft regions that will lift liquid particles to heights above the freezing layer.

Antenna elevation angle is a key parameter for rain loss. As the antenna elevation lowers, a larger portion of the link is in the atmosphere. The importance of the rainfall rate and frequency have been discussed. As can be seen from Figure 3.5, **L** is the length of the communications path from the antenna to the 0°C isotherm layer. **D** is the horizontal component of the slant path. **H** is the height of the 0°C isotherm layer. $\mathbf{H_0}$ is the height of the antenna.

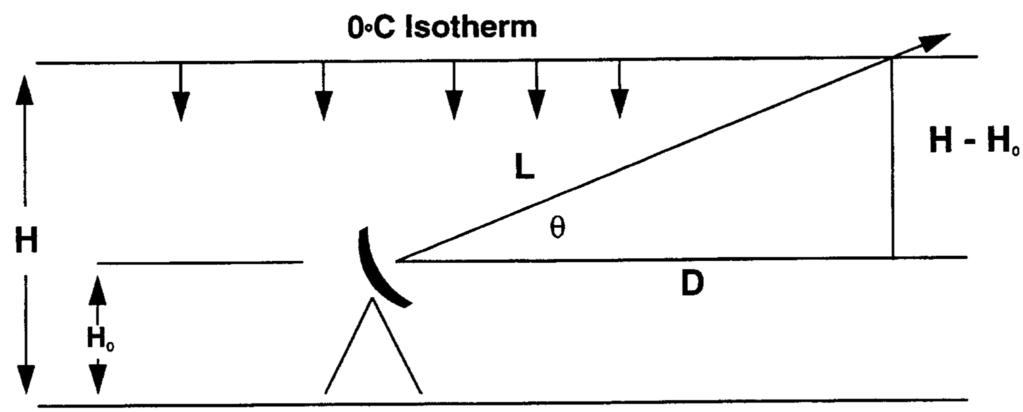

Figure 3.5: Slant Path within the Atmosphere

F. RAINFALL ATTENUATION MODELLING

The question remains, how can a system designer or user predict rain attenuation on a satellite link? At this time, it is not possible to predict the occurrence of a rain event. At some time in the future it may be possible to develop a model for storm development and motion to predict the time, duration and magnitude of a rain event producing attenuation on a satellite link. However, at this time it is common practice to statistically predict the occurrence of such events for a typical month or year. Various models have been developed to relate rainfall data to the probability of satellite link availability per month or year. These models use historical rainfall rates and mathematical models of varying complexity derived from observed attenuation. These historical rainfall rates are

plotted on maps depicting different rain climate zones. The maps used for most models were developed by the Radio Section of the International Telecommunications Union (ITU-R). The two most commonly used models are the International Radio Consultative Committee (CCIR) model and Dr. Robert Crane's Global Model. These models use statistical data for rain rate, measured in millimeters per hour, and their historic occurrence as a percentage of year or month. Other significant models are Dr. Crane's Two Component Model, the ITU-R Model, and an un-published revision to the ITU-R Model called the USA Model. All these models use the ITU-R climate maps except for Dr. Crane's models. Crane's models use maps he has developed.

These rain models are only as accurate as history is in predicting the future. It must be stressed that these models cannot be used to estimate how much an RF signal is being attenuated during a particular rain event. They are tools to predict how available an RF link will be as a percentage of a year given a certain rainfall rate. To work these models, the user must determine the rainfall region the receiver or satellite transmitter is in. This is done by cross referencing the location on a rainfall climate map (Figure 3.6 is an example of an ITU-R climate map). The user determines the rainfall rate for a given percentage of link non-availability for that location for a given year. Table 3.2 shows the rainfall intensity for given percentages given a particular climate zone.

To illustrate this procedure, consider a satellite receiver located in Monterey, CA. Monterey is in rainfall climate zone D. If the link designer wants to determine if the link will be available for 99.99% of the year, he refers to table 2 to find the expected rainfall intensity corresponding to 0.01% of the time. That value is 19 mm/hr. That value, plus the antenna look angle and the height of the 0°C isotherm layer are entered into the selected model to obtain an attenuation value. That value represents an attenuation level he can expect will only be exceeded for 0.01% of the time for that receiver. If the designer had sufficient margin to cover the loss, he can expect that his link will be available 99.99% of the time.

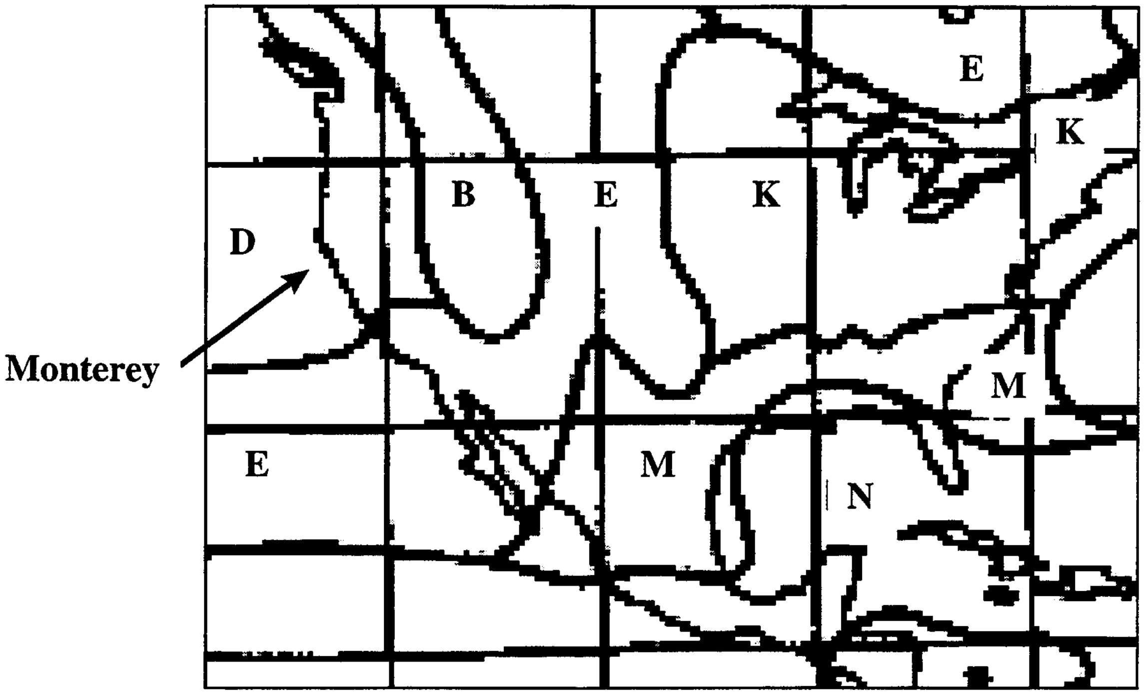

Figure 3.6: ITU-R Rainfall regions for North America
(From Ref. 13)

Percentage	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q
1	<0.1	0.5	0.7	2.1	0.6	1.7	3	2	8	1.5	2	4	5	12	24
0.3	0.8	2	2.8	4.5	2.4	4.5	7	4	13	4.2	7	11	15	34	49
0.1	2	3	5	8	6	8	12	10	20	12	15	22	35	65	72
0.03	5	6	9	13	12	15	20	18	28	23	33	40	65	105	96
0.01	8	12	15	19	22	28	30	32	35	42	60	63	95	145	115
0.003	14	21	26	29	41	54	45	55	45	70	105	95	140	200	142
0.001	22	32	42	42	70	78	65	83	55	100	150	120	180	250	170

Table 3.2: Rain Climate Zones - Rainfall intensity exceeded (mm/hr)
[From Ref. 13]

The particulars of these models are as follows.

1. Crane's Global Model

The Crane Global Model was developed in the early 80's and is still widely used. The model can be used to estimate rain attenuation for terrestrial links as well as slant path lengths, though there is a variation for slant path estimation. The model gives an estimate of rain attenuation during a certain percentage of time over a one year period. The model is a complex function dependent on point rain rate, the vertical extent of rain, and frequency. It is based entirely on meteorological observations, not RF attenuation

measurements. The meteorological observations have shown that there is a relatively uniform attenuation due to rain from the surface to the 0°C isotherm layer. This attenuation is termed the specific attenuation and is measured in decibels-per-kilometer (dB/km). The specific attenuation function is the empirically derived function of frequency and point rain rate presented previously in equation (3.2). The coefficients a and b are frequency dependent and can be estimated by equations (3.3).

Crane observed that the height of the 0°C isotherm layer varies with meteorological conditions. This is reflected in his model. The seasonally and zonally averaged height varies from 4.7 km in the tropics to 3.1 km at 40° latitude to the surface at 61° latitude. The height of the isotherm displays a marked seasonal dependence that, when coupled with the seasonal variation in the occurrence of the higher rain rates, indicates that the 0°C height to be used should depend on latitude and probability of occurrence.

2. Crane's Two Component Model

Crane's Two Component model attempts to better estimate rain attenuation by separately accounting for attenuation due to light rain and attenuation due to heavy rain cells. By observation, Crane noted that the most severe rain is confined to relatively small cells about 6 km in length embedded in larger areas of light rain. Both the Global Model and the Two Component Model utilize maps of climate regions which Crane derived.[Ref. 2]

3. The CCIR Model

The CCIR model was designed specifically for estimating rain attenuation on a slant path and is a less cumbersome method than Crane's models. It uses the effective path length concept similar to that one would use for evaluating attenuation on a terrestrial link. CCIR also uses equation (3.2) and (3.3) to derive specific attenuation. The point rain rates are taken from rain region maps derived by the CCIR (CCIR has since been renamed the Radio section of the International Telecommunications Union (ITU-R)). However all estimates of attenuation are based around an original attenuation estimate for 0.01% of the year. Estimates of attenuation for different percentages of the year are derived from this basis by

$$A_P = A_{0.01}\,(.12)\,(p)^{-(0.546 + 0.043 \log p)} \qquad (3.4)$$

where p is the percentage of time you are interested in.

4. The ITU-R Model

The ITU-R model, published in 1991, is an improvement to the CCIR model. It adjusts the isotherm height and adds a horizontal adjustment factor.

5. The USA Model

The USA model has yet to be formally published. It is a proposed improvement to the ITU-R model and was submitted to the ITU for consideration in January 1993. The authors prefer to call it the DAH model in reference to their initials: Dissanayake, Allnutt, and Haidara. It was developed to remedy deficiencies in the ITU-R model in estimating rain attenuation in heavy rainfall regions. There is a very interesting anomaly in this model. As the ground station moves farther from the satellites nadir, the elevation angle decreases and the amount of the path within the atmosphere increases. With this model, this holds true only as the ground station moves either east or west. As the ground station moves north and south, this model adjusts the height of the freezing layer. As one would expect, above 23 degrees north or south, the height of the freezing layer lowers. Thus the effective path length below the freezing layer actually decreases. It replaced the horizontal and vertical path reduction factors with two path adjustment factors. The CCIR, ITU-R and USA model all base attenuation estimates around a 0.01% attenuation exceedence. It is only considered valid for rainfall attenuation percentages from 1% to 0.001%. However, the USA model has revised the probability extrapolation. This model will be discussed in detail in section H.[Ref. 12]

G. JPL PROPAGATION STUDIES

A key deficiency in all these rain models is the fact that they were developed before the wide-spread use of RF links in the K/Ka band. Whereas there exists a body of experimental data to confirm attenuation at C and Ku bands, data at K/Ka band

frequencies are scarce. Existing prediction models appear to lose their robustness when applied to K/Ka band frequencies.

In September of 1993, NASA launched the Advanced Communications Technology Satellite (ACTS). Parked in a geostationary orbit near 100 degrees west, ACTS is supporting both communication and propagation experiments. It has a 20.185 GHz down-link (K-band) and a 27.505 GHz up-link (Ka-band). ACTS is providing an opportunity to study precipitation attenuation on earth-space communications at K/Ka band and to develop techniques to counter them. The Jet Propulsion Laboratory (JPL) initiated the ACTS Propagation Campaign to acquire a lasting base of 20/30 GHz propagation data for attenuation model development. The experiment has been going on for more than two years. JPL is studying the effects of rain attenuation on the ACTS signal at seven sites across the U.S. and Canada. These sites were purposely selected to cover a wide range of climate zones. ACTS propagation campaign plans and results are deliberated at workshops twice per year.

The most recent workshop, the IX ACTS Propagation Workshop, was held in November of 1996. At this workshop, Glenn Feldhake of Stanford Telecom presented the results of a study comparing the accuracy of 11 rain models in predicting rain attenuation of the ACTS signal. This study was a follow-up to one conducted by an ITU-R working party in June of 1996. The rain models tested included Crane's Global model, his more recent Two Component Model, the CCIR model, the ITU-R model and the USA model. Stanford Telecom compared two years of ACTS propagation data from the seven sites of the JPL propagation study to these models. Crane's maps were used for the Global and Two Component models and the ITU-R maps were used for the others. [Ref. 21]

In both studies, the evaluators measured various attenuation levels on the satellite link, then associated that attenuation with the percentage of year that should have been expected. The error between predicted and measured attenuation was computed as follows: % Error = $100*(A_{Predicted}-A_{Measured})/A_{Measured}$. The studies derived errors for rainfall rates for the following percentages of the year: 1%, 0.5%, 0.3%, 0.2%, 0.1%, 0.05%, 0.03%, 0.02%, 0.01%, 0.005%, 0.003%, 0.002% and 0.001%. Only measured attenuation values less than 20 dB were considered.[Ref. 21]

In both studies the USA Model performed the best. In the ITU study, the USA Model had the lowest RMS error overall, had the lowest RMS error in 14 of 22 tests, and proved to be the most consistent across all tests. In the Stanford Telecom Study, the USA Model also had the lowest RMS error for both the ACTS up-link and down-link, and had

the best performance for three of the seven test sites. JPL and Stanford Telecom haven't determined why various models perform better than others. However, as can be seen from Table 3.3, the prediction error of all these models, to include the USA Model, is high.[Ref. 21]

20 GHz

USA	39.16
ExCell	43.11
ITU-R	48.10
TC	48.61
Global	49.09
CCIR	50.56
Brazil	50.96
Japan	53.93
Spain	59.84
SAM	62.17
Leitao	66.91

27 GHz

USA	32.18
ExCell	35.12
TC	39.03
ITU	41.37
CCIR	43.89
Global	45.88
Brazil	46.47
Japan	50.58
Spain	55.10
SAM	56.63
Leitao	60.20

Table 3.3: Results of Stanford Telecom Study - RMS Error

H. THE USA RAIN PREDICTION MODEL

As the USA model is demonstratedly the best model developed so far for estimating rainfall attenuation, I will present it in detail. Remember that this model is only valid for rainfall percentages from 1% to 0.001%. (Taken from Proposed Amendment to ITU-R Recommendation 618 - Prediction of Rain Attenuation, ITU-R Document 5C/56E, 05 January 1993, (Dissanayake A.W., Allnutt J.E., and Haidara), Ref. 11)

1. Determine the height of the 0°C isotherm layer (Hfr) using the ground station latitude, ϕ:

$$\text{Hfr} = 5.0 \qquad \text{for } 0 \le \phi < 23^{\circ}$$

$$\text{Hfr} = 5.0 - 0.075\,(\phi - 23^{\circ}) \qquad \text{for } \phi \ge 23^{\circ} \qquad (3.5)$$

2. Determine the slant-path length, Ls below the 0°C isotherm layer:

$$L_s = (H_{fr} - H_s)/\sin\theta \qquad (3.6)$$

where θ is the antenna elevation angle and Hs is the station height in km. This formula is valid down to $\theta = 5^{\circ}$.

3. Determine the horizontal projection, L_G, of the slant path length:

$$L_G = L_s \cos\theta \qquad (3.7)$$

4. Obtain the rain intensity, $R_{0.01}$ (mm/hr) exceedence for 0.01% of an average year and calculate the specific attenuation A (dB/km), using the frequency coefficients a and b given in Table I of ITU-R report 72.

$$A = a(R_{0.01})^{b} \quad \text{(dB/km)} \qquad (3.8)$$

5. Calculate the horizontal path adjustment factor, $rh_{0.01}$, for 0.01% of the time:

$$rh_{0.01} = 1 / (1 + 0.78\, (L_G\, A / F)^{.5} - 0.38\, (1\text{-}\exp(-2L_G)\,)\,) \qquad (3.9)$$

where F is frequency in GHz.

6. Calculate the adjusted rainy path length, Lr (km) through rain:

$$L_r = L_G\, rh_{0.01} / \cos\theta \qquad \text{for } \zeta > \theta$$

$$L_r = Hfr - Hs / \sin\theta \qquad \text{for } \zeta \leq \theta \qquad (3.10)$$

$$\text{where } \zeta = \tan^{-1} (Hfr - Hs / L_G\, rh_{0.01}) \qquad (3.11)$$

7. Calculate the vertical reduction factor $rv_{0.01}$, for 0.01% of the time:

$$rv_{0.01} = 1 / (\, 1 + (\sin\theta\,)^{.5}\, (31(1 - \exp(-\theta / [1 + |\, \phi\; - 36|]\,))\;\; ((L_r A)^{.5} / F^2) - 0.45)) \qquad (3.12)$$

8. The effective path length through rain, L_e (km), is given by:

$$L_e = L_T \, rv_{0.01} \quad \text{(km)} \tag{3.13}$$

9. The attenuation exceeded for 0.01% of an average year may then be obtained from:

$$A_{0.01} = A \, L_e \quad \text{(dB)} \tag{3.14}$$

10. The attenuation to be exceeded for other percentages of an average year , in the range 0.001% to 1.0%, may be estimated from the attenuation to be exceeded for 0.01% for an average year by using:

$$A_p = A_{0.01} \, (p/0.01)^{-(0.655 + 0.033 \ln p - 0.045 \ln A0.01 - z \sin \theta \, (1-p))} \tag{3.15}$$

where p is the percentage of interest and z is given by:

$$z = -0.005 \, (\phi - 36) \qquad \text{for } \theta \geq 20^{\circ}$$

$$z = -0.005 \, (\phi - 36) + 2.05 - 6 \sin \theta \qquad \text{for } \theta < 20^{\circ} \tag{3.16}$$

where ϕ is the ground station latitude.

11. Table 3.4 shows some USA derived attenuation exceedence values for a receiver in Monterey receiving the 20.7 GHz downlink from UFO 8 (to be launched in a geosynchronous orbit at 172 E in January 98).

Percentage of year	Attenuation (dB)	ΔT
1	1.8	92.6
0.2	3.27	144.4
0.1	5.04	187.5
0.02	13.49	260.7
0.001	56.83	272.9

Table 3.4: Attenuation for various percentages of year in dB and increase in antenna temperature in degrees Kelvin.

I. RAIN AND ANTENNA TEMPERATURE

So far this study has only addressed the issue of rain directly reducing the signal power. However, rain also affects system noise temperature by increasing sky noise temperature, thus decreasing the receiver figure of merit, G/T, where G is the antenna gain and T is the system temperature, T_{sys}. T_{sys} is the antenna temperature plus the equivalent temperature of the receiver. T_{sys} during rain is increased by

$$\Delta T = Tr(1 - 1/Lr) \qquad (3.17)$$

where Lr is the value from equation (3.15). When the attenuation Lr is high, ΔT is nearly equal to the rain temperature Tr. In practice, Tr is usually taken to be 273 K. [Ref. 8:p. 166.] ΔT for Monterey is shown in Table 3.4.

J. SUMMARY

This chapter covered in detail atmospheric factors which will affect the performance of GBS Phase II. The next chapter will update the UFO 8 link budget for the Korean theater developed in Chapter II, incorporating atmospheric losses. The link budget will show that the links for the 24 Mbps and the T1 data streams will not be available 99% of the time due to atmospheric losses. Chapter IV will discuss UFO 8 data rates for the various data streams which can be supported for a 99% link availability for the Korean theater.

IV. EXPECTED GBS SUPPORTABLE DATA RATES FOR THE KOREAN THEATER FROM UFO 8

In Chapter II we developed a link budget for UFO 8 support to the Korean theater assuming a worst case satellite position, i.e. when the satellite is at its southern most position. The link budget (Table 2.7) is reprinted here for convenience.

24 Mbps Spot Beam

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.22	dB
Rain Loss	0.00	dB
Atmoshpheric Loss	0.00	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	95.93	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.43	dB
Rain Loss	0.00	dB
Atmospheric Loss	0.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	16.00	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	86.84	sB-Hz
C/N0 Total	86.34	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	12.61	dB
Required Eb/N0	6.50	dB
Margin	6.11	dB

6 Mbps Theater Injected

UPLINK		
EIRP	78.00	dBW
Free Space Loss	213.91	dB
Rain Loss	0.00	dB
Atmospheric Loss	0.00	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	94.24	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.51	dB
Rain Loss	0.00	dB
Atmoshperic Loss	0.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	16.00	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	86.76	sB-Hz
C/N0 Total	86.05	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	18.14	dB
Required Eb/N0	6.50	dB
Margin	11.64	dB

1.544 Mbps Area Beam

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.31	dB
Rain Loss	0.00	dB
Atmospheric Loss	0.00	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	95.84	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.56	dB
Rain Loss	0.00	dB
Atmoshperic Loss	0.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	16.00	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	74.21	sB-Hz
C/N0 Total	74.18	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	12.29	dB
Required Eb/N0	6.50	dB
Margin	5.79	dB

Table 2.7: UFO 8 Link Budgets for the Korean theater; transponders 2-4.

As shown above, the margins are sufficient to close the links to Korea. However, these link budgets don't account for atmospheric losses. As mentioned, with UFO 8's orbital drift, the elevation angle as computed by equation (2.15) varies from 11.24 to 8.27 degrees for the Camp Roberts PIP and from 31.9 to 25.045 degrees for the Korea GRT. Due to this elevation variation, the atmospheric absorption will vary from 1.4 dB to 2 dB for the up-link and 1.6 dB to 2.0 dB for the down-link. Using the more precise STK software, the elevation angles are found to actually vary from 13.6 to 6.0 degrees for the up-link and 31.2 to 21.6 degrees for the down-link. The corresponding worst case atmospheric losses are 2.8 dB for the up-link and 2.29 dB for the down-link. These losses are for August, when the average water vapor density for Korea is approximately 20 g/m3 and 10 g/m3 for California.

A. SUPPORTABLE DATA RATES TO KOREA, PIP LOCATED AT CAMP ROBERTS

To show the expected GBS performance accounting for atmospheric losses abbreviated link budgets for transponders 2-4 are presented in table 4.1, using values from Table 2.7. These link budgets account for atmospheric losses during August assuming a receive terminal and TIP located in Korean and a PIP located in Camp Roberts. The USA model was used to estimate rain losses expected for 1% of the year, or for a 99% link availability. The link budgets also account for the increase in GRT noise temperature due to rain loss.

	Transponder 2		Transponder 3		Transponder 4	
C/No up clear WX	95.93	dBW	94.24	dBW	95.84	dBW
gaseous absorption	2.80	10 g/m3	2.29	20 g/m3	2.80	10 g/m3
Rain attenuation	4.93	dB	4.87	dB	5.10	dB
C/No adjusted	88.20	dBW	87.08	dBW	87.94	dBW
C/No down clear WX	86.34	dBW	86.26	dBW	73.31	dBW
Clear WX G/T	16.00	dB/K	16.00	dB/K	16.00	dB/K
G/T for 1% rain loss	14.31	dB/K	14.30	dB/K	14.29	dB/K
gaseous absorption	2.29	20 g/m3	2.29	20 g/m3	2.29	20 g/m3
Rain attenuation	2.11	dB	2.12	dB	2.15	dB
C/No adjusted	80.25	dBW	80.15	dBW	67.16	dBW
C/No Total	79.60	dBW	79.35	dBW	67.12	dBW
Data Rate (Mbps)	2.36E+07		6.18E+06		1.54E+06	
Data Rate (dB-bps)	73.73	dB-Mbps	67.91	dB-Mbps	61.89	dB-Mbps
Achieved Eb/No	5.88	dB	11.44	dB	5.24	dB
Required Eb/No	6.50	dB	6.50	dB	6.50	dB
Margin	-0.62	dB	4.94	dB	-1.26	dB

Table 4.1: Abbreviated link budget for UFO 8.

As can be seen, with 20 g/m3 water vapor content expected for Korea during August, and a 1% expected rainfall loss, the links for transponders 2 and 4 will not close 99% of the time. Further complicating matters is the fact that this budget assumes a 1.4

dB noise figure receiver. This is estimated to be a very expensive receiver, with an expected cost of $24K per unit.[Ref. 15]

B. SUPPORTABLE DATA RATES TO KOREA, PIP LOCATED IN HAWAII

Thus far, we have assumed that the PIP for UFO 8 will be located at Camp Roberts, CA, one of the two potential sites considered for the UFO 8 PIP. Hawaii is the second possible PIP site. Having considered GBS performance for Camp Roberts, lets now consider the case where the PIP at Hawaii. As this will only change the up-link parameters for the 24 Mbps spot beam and the 1.544 Mbps Area Beam, only these two link budgets are presented in Table 4.2. As Hawaii is considerably close to the satellites nadir, the elevation angle will increase, ranging from 51.94 to 43.57 degrees. The worst case atmospheric loss will be only .77 dB. Hawaii has a lower rainfall average. Coupling this with the higher elevation angle to the satellite results in a lower expected rain loss. As can be seen, by locating the PIP in Hawaii we are able to close the link for 99% of the time for transponder 2 (24 Mbps spot beam) and can almost close the link for transponder 4 (1.544 Mbps area beam).

Transponder 2

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.54	dB
Rain Loss	1.88	dB
Atmoshperic Loss	0.77	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	93.96	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.43	dB
Rain Loss	2.11	dB
Atmospheric Loss	2.29	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	14.31	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	80.75	sB-Hz
C/N0 Total	80.55	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	6.82	dB
Required Eb/N0	6.50	dB
Margin	0.32	dB

Transponder 4

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.59	dB
Rain Loss	1.90	dB
Atmospheric Loss	0.78	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	93.88	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.56	dB
Rain Loss	2.15	dB
Atmoshperic Loss	2.29	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	14.29	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	68.06	sB-Hz
C/N0 Total	68.05	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	6.16	dB
Required Eb/N0	6.50	dB
Margin	-0.34	dB

Table 4.2: UFO 8 link budget for PIP located in Hawaii; transponder 2 and 4.

C. RECIEVER FOM AND CORRESPONDING SUPPORTABLE DATA RATES

This analysis has assumed a receiver with a 22 inch diameter antenna and a receiver with a 1.4 dB noise figure, having a clear weather figure of merit (FOM) of 16 dB/K. As mentioned, a receiver with a 1.4 dB noise figure is an expensive receiver, estimated to cost around $24K. Furthermore, a 22 inch antenna may not be a viable option for some of the Navy's smaller ships. Let's now consider a receiver with a smaller antenna, 18 inches, with a lower cost receiver having a 2.5 dB noise figure. This would give the receive terminal a FOM of 12.5 dB/K in clear weather and 11.3 dB/K with

approximately 2.11 dB of rain attenuation. As can be seen in Figure 4.1, with rain on the up-link, the link will support the full data rate with clear weather on the down-link but will support less than 14 Mbps if there is rain on the down-link. For the T1 Area coverage beam, the link will close for the full data rate clear weather on the down-link but will only support a data rate less than 750 Kbps if there is rain on the down link. This is illustrated in Figure 4.2. Again, this assumes a 99% link availability given historical rainfall rates for the Korean theater. This roughly equates to a rainfall rate of less than one half inch of rain per hour, fairly light rain.

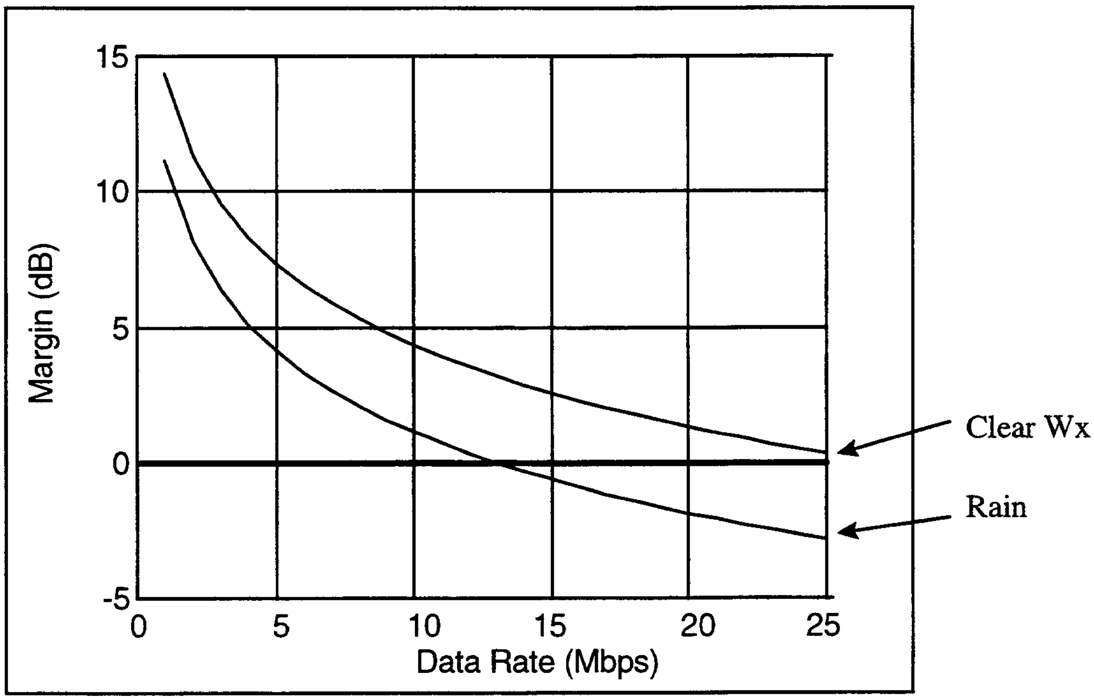

Figure 4.1 Supportable Data Rates from UFO 8 to Korea; Transponder 2, 18 inch receive antenna, 2.5 dB noise figure, rain on Up-Link

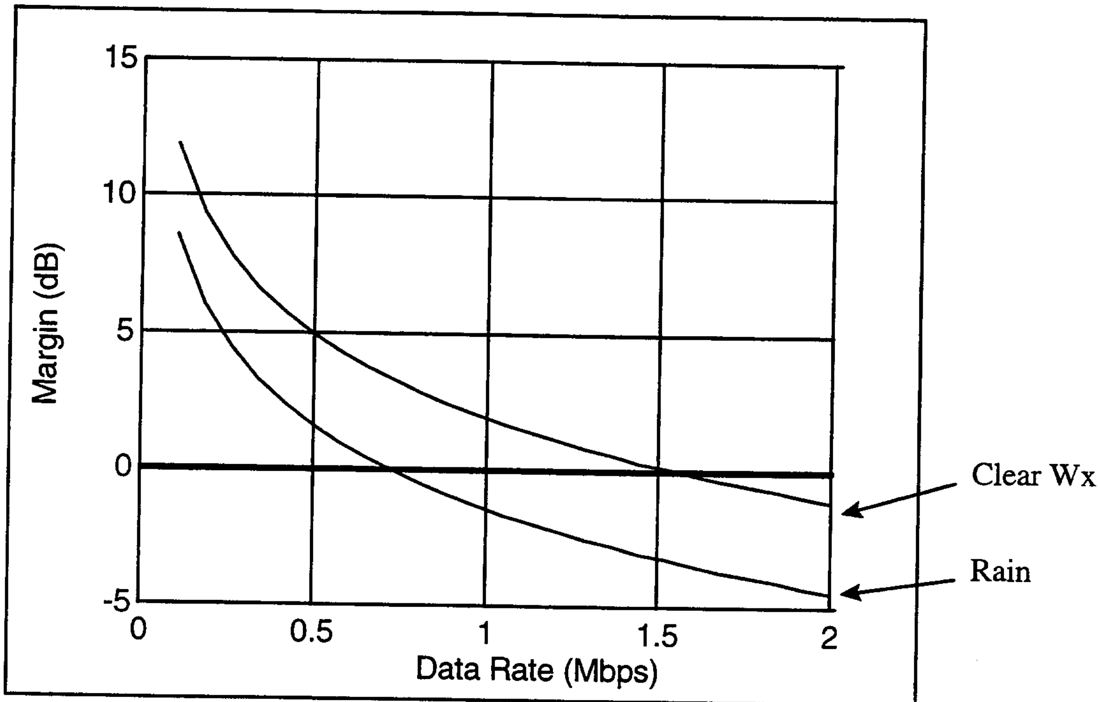

Figure 4.2 Supportable Data Rates from UFO 8 to Korea; Transponder 4, 18 inch receive antenna, 2.5 dB noise figure, rain on Up-Link

For higher rainfall rates it is still possible to close the link, provided that the data rate is further reduced. Recall from the previous chapter, to achieve a higher annual link availability requires the link to be able to compensate for higher rainfall losses. Figures 4.3 and 4.4 show supportable data rates for 99.5, 99.7 and 99.8 annual link availability for the 24 Mbps Spot Beam and T1 area coverage beam, respectively. These annual percentages equates roughly to rainfall rates of 1 to 3 inches of rainfall per hour for the Korean theater. As can be seen, to maintain the link for higher rainfall, GBS must be able to vary its data rate.

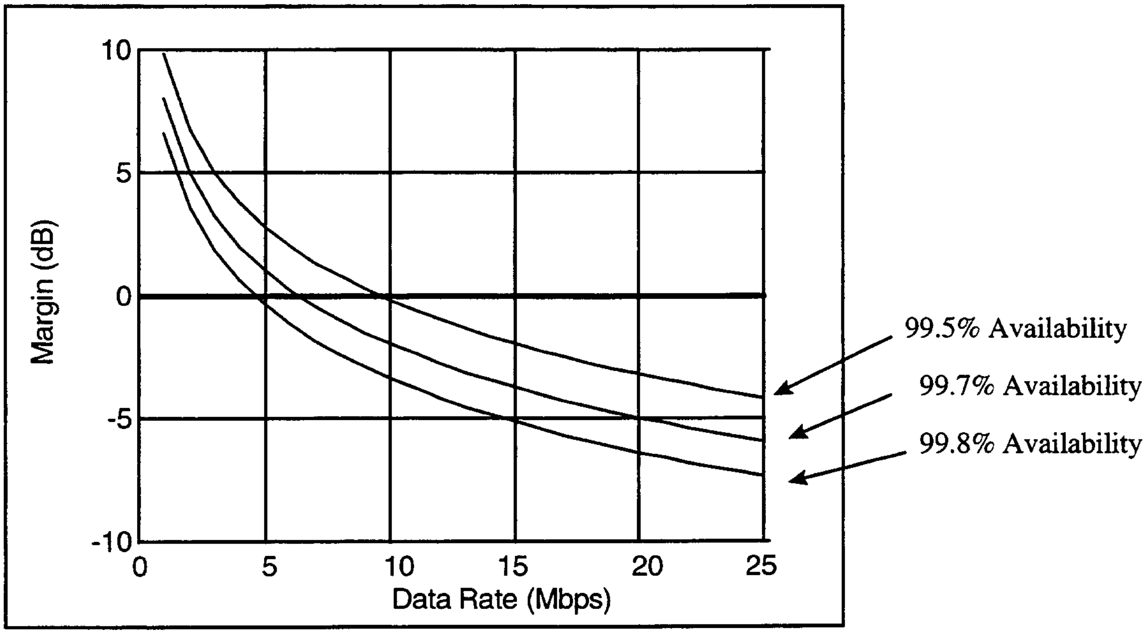

Figure 4.3 Supportable Data Rates for Transponder 2 for other rainfall percentages, 18 inch receive antenna, 2.5 dB noise figure, rain on up-link

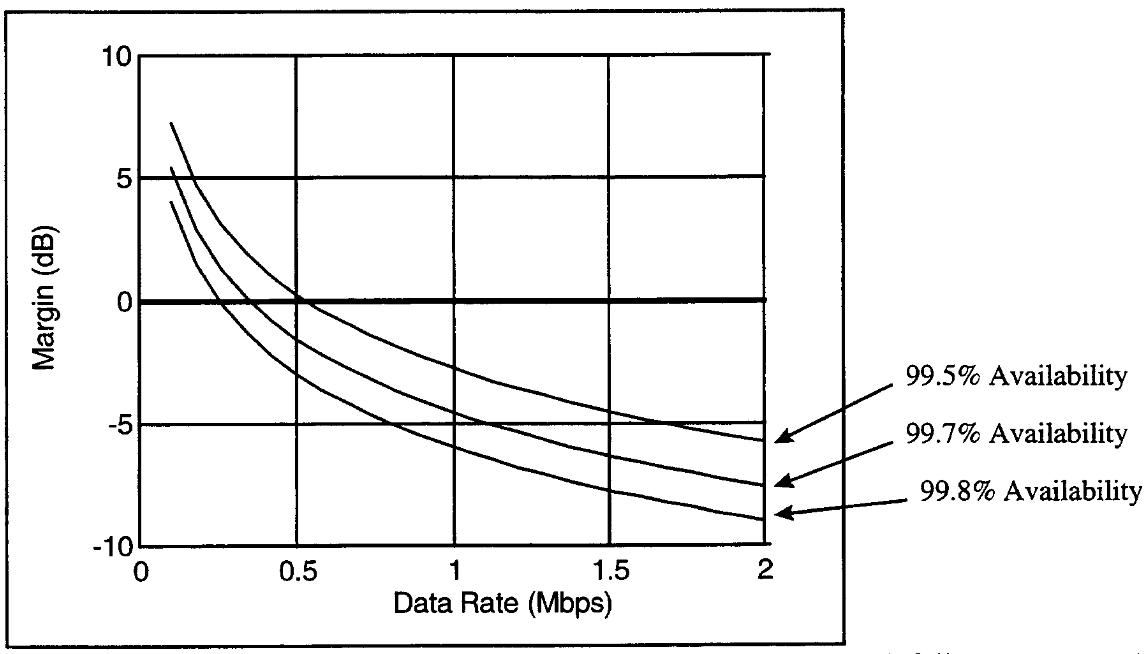

FIGURE 4.4 Supportable Data Rates for Transponder 4 for other rainfall percentages, 18 inch receive antenna, 2.5 dB noise figure, rain on up-link

D. SUMMARY

This chapter focused on the expected supportable data rates from the GBS package aboard UFO 8 to the Korean theater. The next chapter will consider supportable data rates from the GBS package aboard UFO 9 to the Mediterranean, Caribbean, and the Arabian Gulf.

V. EXPECTED PERFORMANCE FOR UFO 9

A. UFO 9 ACCESS AREA

Thus far we have concentrated on the performance of the GBS package aboard UFO 8. This chapter will consider the GBS package aboard UFO 9. UFO 9 is to be located at 22.5W giving it coverage of the eastern portion of the U.S., South America, Europe, Africa, and the Middle-East. Figure 5.1 shows the access area for UFO F9, with spot beams centered at 39 13.8N/10 53.4E (the central Mediterranean) and 26 34.8N/51 03.6E (the central Arabian Gulf), and an area coverage beam centered at 18 27.6N/82 22.2 W (the central Caribbean).

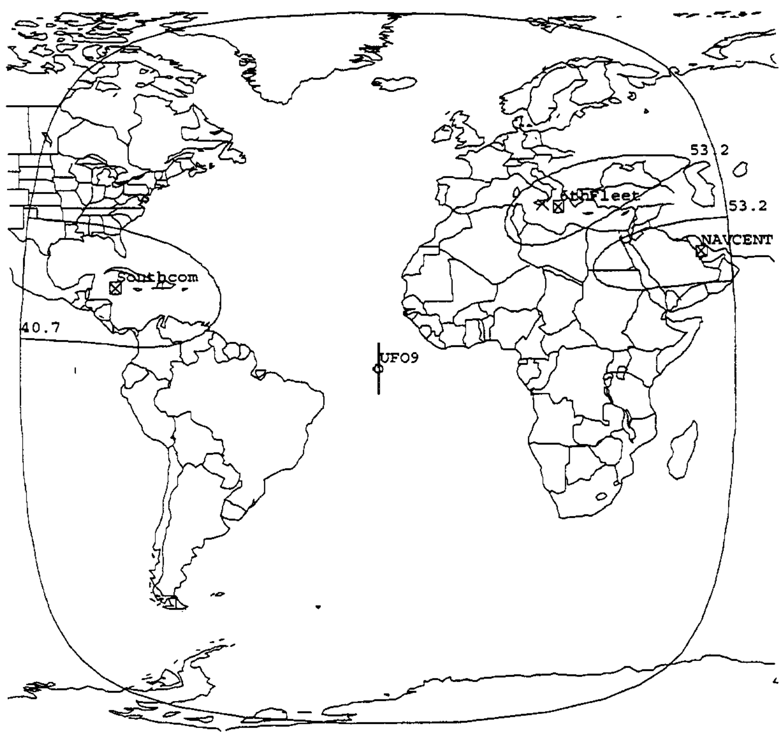

Figure 5.1: GBS UFO 9 IAA

As with UFO F8, UFO F9 will have an inclined orbit of 6 degrees. Figure 5.2 and 5.3 shows UFO F9's access areas at 6 and 18 hours after nadir (the maximum and minimum points of its orbital drift).

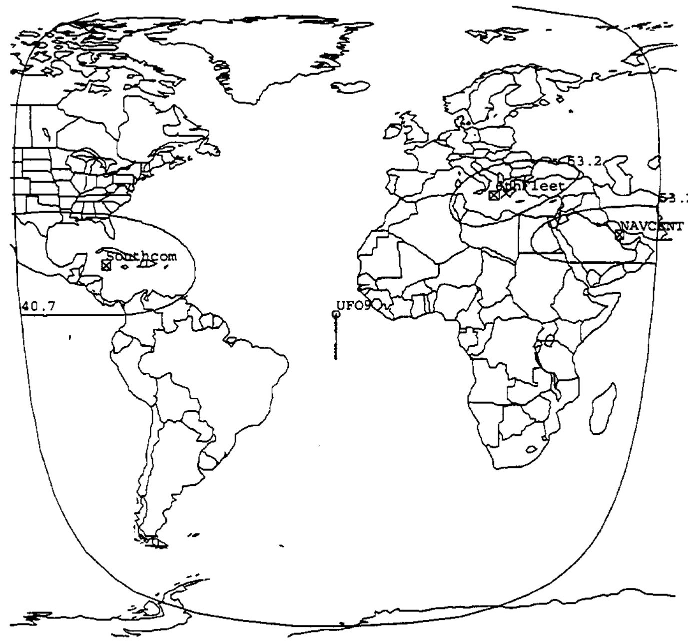

Figure 5.2: UFO 9 6 hours after crossing nadir: UFO 9's northern most point.

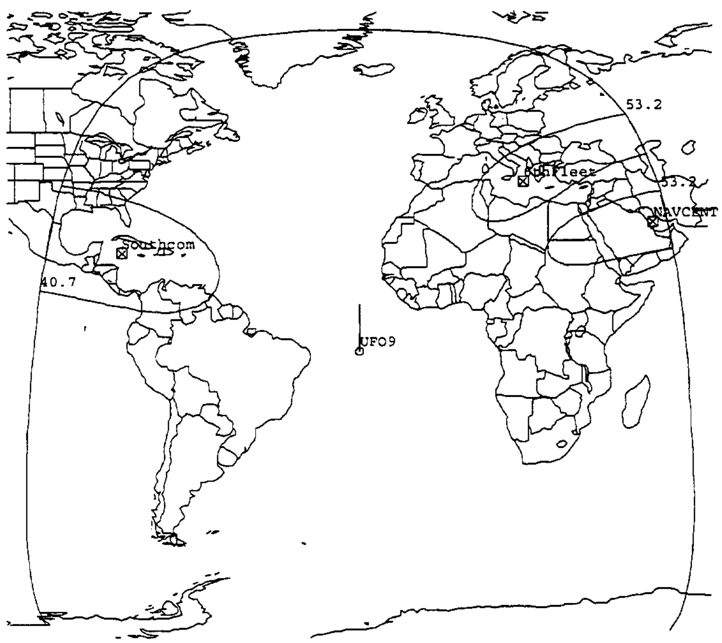

Figure 5.3: UFO 9 18 hours after crossing nadir: UFO 9's southern most point.

The PIP for UFO 9 will be located in Sigonella, Italy (37 24 N/14 55.2 E). The antenna elevation angle from Sigonella to UFO 9 ranges from 36.7 to 26.6 degrees and

the corresponding atmospheric loss, given the average water vapor content for August of 15 g/m3 for the central Mediterranean, ranges from .69 dB to .92 dB for the transponder 2 up-link (30.215 GHz). Two receivers will be considered for this analysis. The first will have a 22 inch antenna and a 1.4 dB noise figure LNA, giving it a clear weather FOM of 16 dB/K. The second receiver will have an 18 inch antenna and a 2.5 dB noise figure LNA, giving it a clear weather FOM of 12.5 dB/K. This analysis will not specifically address transponder 1 as this data stream is transmitted via the same spot beam as transponder 2, at a slightly lower frequency.

B. SUPPORTABLE DATA RATES FOR THE MEDITERRANEAN

For the analysis of supportable data rates for the Mediterranean, the TIP is assumed to be at Sigonella, collocated with the PIP. The UFO 9 antenna boresite will be aimed at the central Mediterranean (39 13.8 N/ 10 53.37 E). (see Figure 5.4) The receive antenna elevation will vary from 38.38 to 27.58 degrees over a 24 hour period will a corresponding atmospheric loss of 1.03 to 1.38 dB.

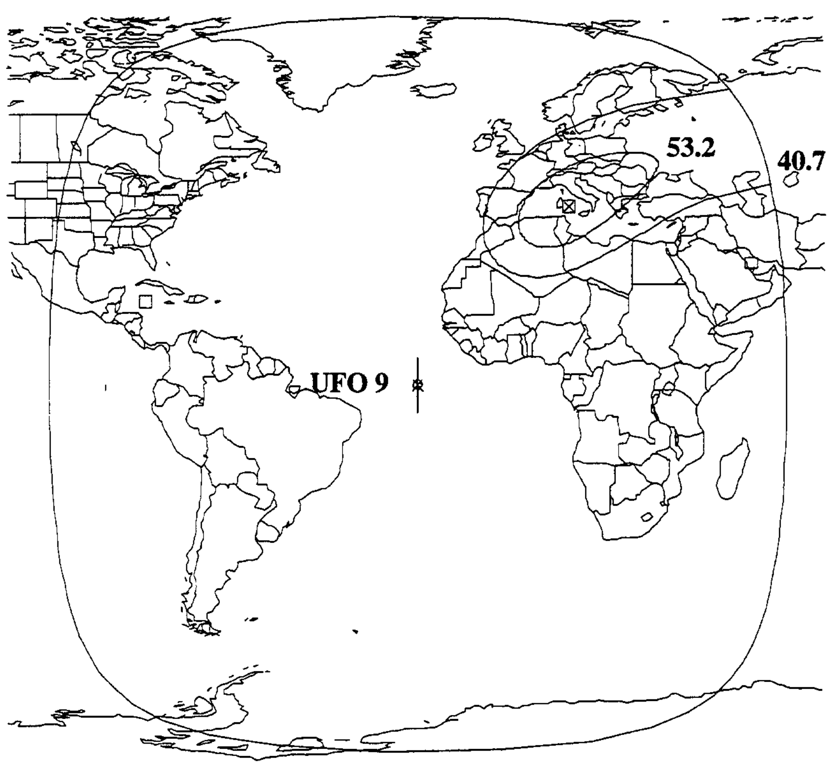

Figure 5.4: UFO 9 spot beam and area coverage beam focused on the central Mediterranean.

The receiver FOM for 1% annual rainfall for the Mediterranean for the 16 dB/K receiver is 14.44, 14.43, and 14.42 dB/K for transponder 2, 3 and 4, respectively. For the lower FOM receiver, the FOM for 1% annual rainfall is 11.4, 11.39, and 11.39 dB/K, for transponder 2, 3, and 4 respectively. As can be seen from Table 5.1, with the higher FOM receiver, the links will close for the maximum data rate for all channels. However, for the lower FOM receiver, the link will not close for the maximum data rate for transponder 2 and 4. (see Table 5.2)

Transponder 2

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.85	dB
Rain Loss	4.53	dB
Atmoshperic Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.85	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.42	dB
Rain Loss	1.87	dB
Atmospheric Loss	1.38	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	14.44	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	82.04	sB-Hz
C/N0 Total	81.51	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	7.78	dB
Required Eb/N0	6.50	dB
Margin	1.28	dB

Transponder 3

UPLINK		
EIRP	78.00	dBW
Free Space Loss	213.87	dB
Rain Loss	4.58	dB
Atmospheric Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	88.78	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.45	dB
Rain Loss	1.88	dB
Atmoshperic Loss	1.42	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	14.43	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	81.95	sB-Hz
C/N0 Total	81.13	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	13.22	dB
Required Eb/N0	6.50	dB
Margin	6.72	dB

Transponder 4

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.90	dB
Rain Loss	4.55	dB
Atmospheric Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.78	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.50	dB
Rain Loss	1.90	dB
Atmoshperic Loss	1.48	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	14.42	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	70.79	sB-Hz
C/N0 Total	70.75	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	8.86	dB
Required Eb/N0	6.50	dB
Margin	2.36	dB

Table 5.1: UFO 9 Link Budgets for the central Med.; transponder 2-4, 22 inch receive antenna, 1.4 dB noise figure, 1% annual rainfall.

Transponder 2

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.85	dB
Rain Loss	4.53	dB
Atmoshperic Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.85	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.42	dB
Rain Loss	1.87	dB
Atmospheric Loss	1.38	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	11.40	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	79.00	sB-Hz
C/N0 Total	78.73	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	5.00	dB
Required Eb/N0	6.50	dB
Margin	-1.50	dB

Transponder 3

UPLINK		
EIRP	78.00	dBW
Free Space Loss	213.87	dB
Rain Loss	4.58	dB
Atmospheric Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	88.78	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.45	dB
Rain Loss	1.88	dB
Atmoshperic Loss	1.42	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	11.39	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	78.91	sB-Hz
C/N0 Total	78.48	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	10.57	dB
Required Eb/N0	6.50	dB
Margin	4.07	dB

Transponder 4

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.90	dB
Rain Loss	4.55	dB
Atmospheric Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.78	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.50	dB
Rain Loss	1.90	dB
Atmoshperic Loss	1.48	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	11.39	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	67.76	sB-Hz
C/N0 Total	67.74	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	5.85	dB
Required Eb/N0	6.50	dB
Margin	-0.65	dB

Table 5.2: UFO 9 Link Budgets for the central Med.; transponder 2-4, 18 inch receive antenna, 2.5 dB noise figure, 1% annual rainfall.

Figures 5.5, 5.6 and 5.7 show the supportable data rates for transponder 2, 3, and 4 respectively. As can be seen, for the lower FOM receiver, the data rate will have to be lower than 15 Mbps for transponder 2 and lower than 1 Mbps for transponder 4 to have a margin of 2 dB.

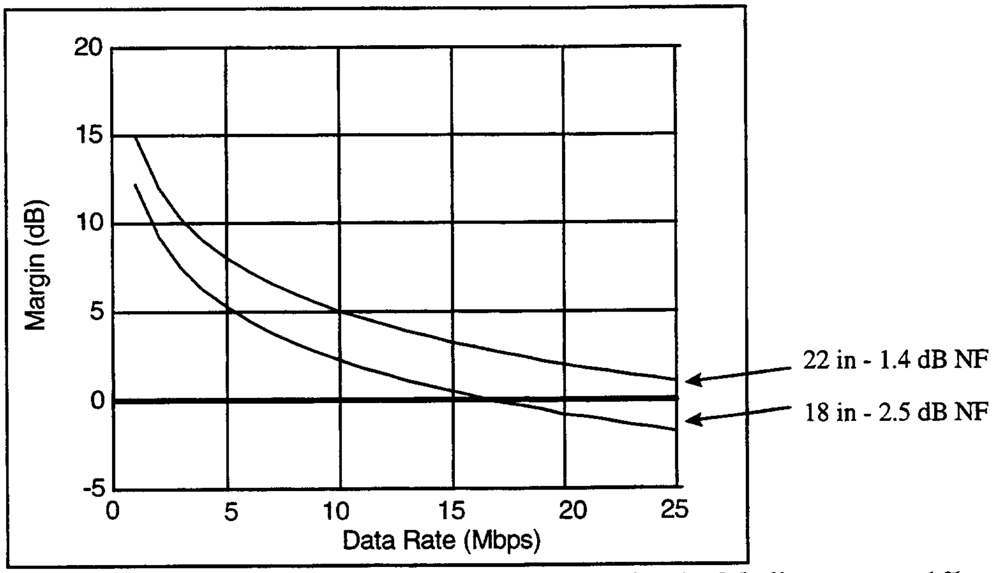

Figure 5.5: Supportable data rates for transponder 2 for the Mediterranean; 1% annual rainfall.

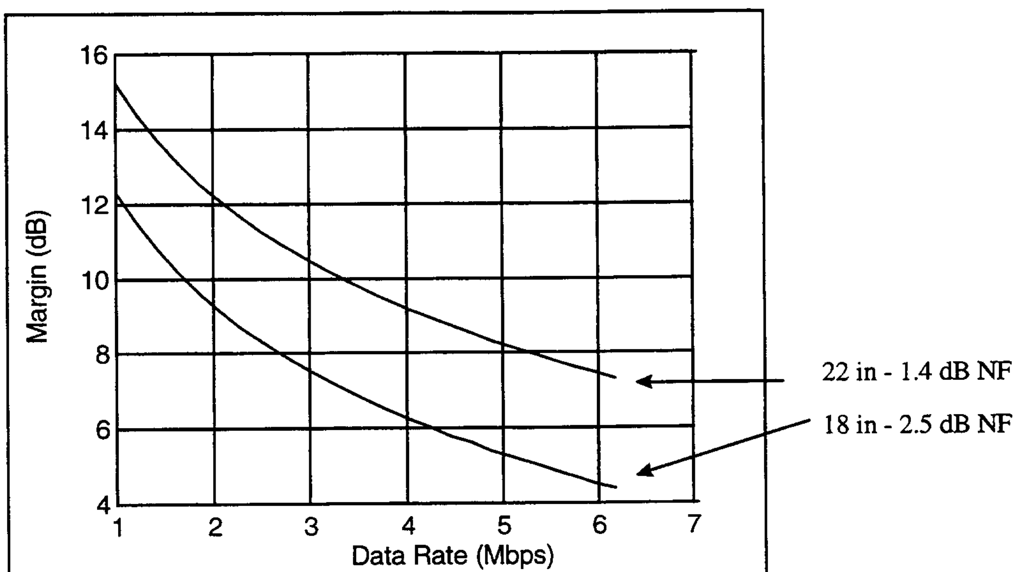

Figure 5.6: Supportable data rates for transponder 3 for the Mediterranean; 1% annual rainfall.

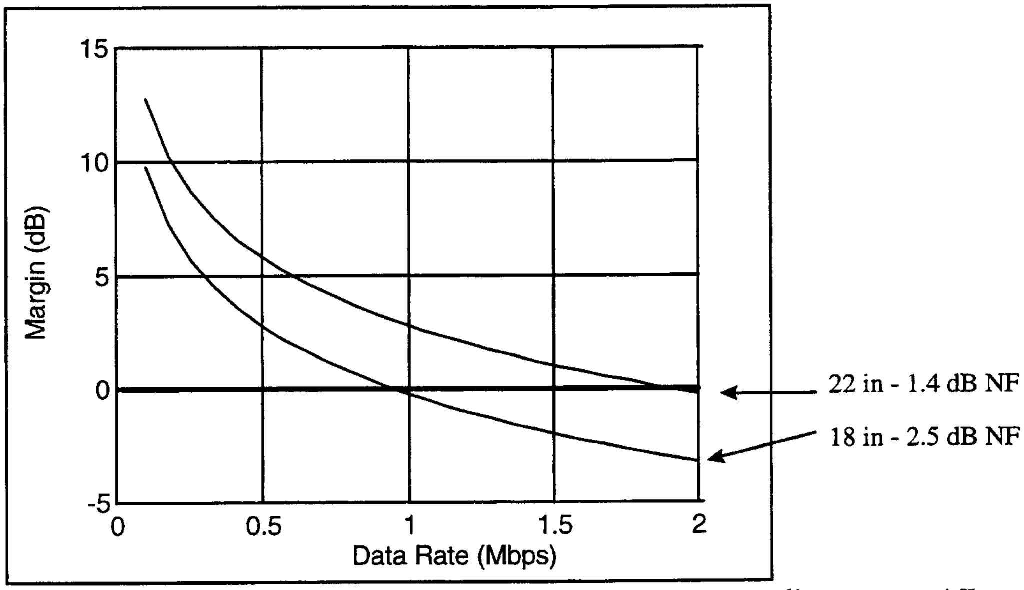

Figure 5.7: Supportable data rates for transponder 4 for the Mediterranean; 1% annual rainfall.

C. SUPPORTABLE DATA RATES FOR THE CARIBBEAN

For the Caribbean link, the UFO 9 antenna boresite will be aimed at 18 27.6 N/ 82 22.2 W (see Figure 5.8). The receiver antenna elevation angle from boresite will range from 22.4 to 17.8 degrees. The atmospheric losses will be worse in this case as the average water vapor content for the Caribbean in August is 20 g/m3. The expected atmospheric absorption will be from 2.38 to 2.96 dB.

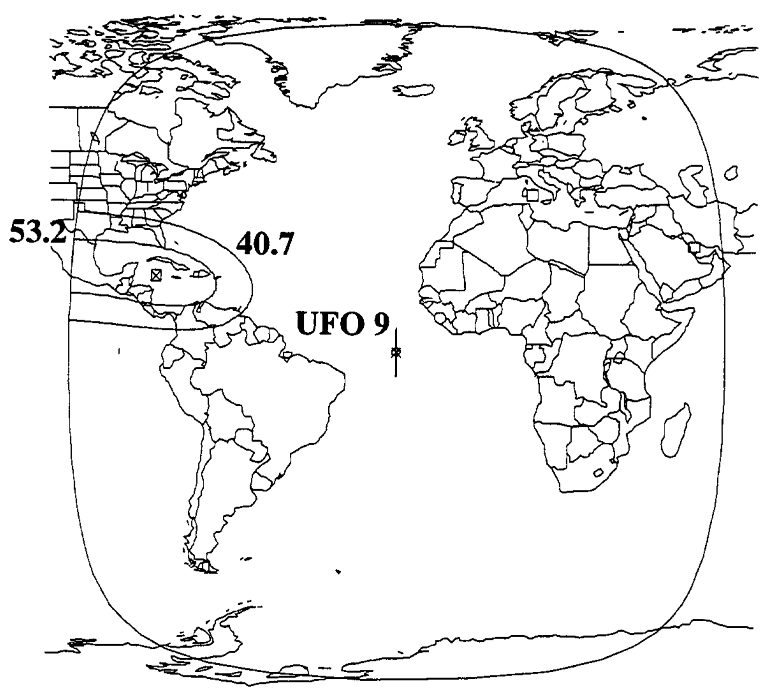

Figure 5.8: UFO 9 spot beam and area coverage beam focused on the central Caribbean.

As with the central Mediterranean, this analysis will consider a receiver with a FOM of 16 dB/K for clear weather as well as a receiver with a 12.5 dB/K FOM. For transponder 3, the theater injected spot beam, the TIP is assumed to be located in Miami. The elevation angle from the TIP to UFO 9 ranges from 23.6 to 17.26 degrees with a corresponding atmospheric absorption loss of 1 to 1.4 dB. As can be seen from Tables 5.3 and 5.4, due to the combination of low elevation angle to the satellite, high water vapor content and tropical rainfall rates, UFO 9 will not support the full data rate of GBS for either receiver for a 99% link availability for transponders 2 and 4. As can be seen from Figures 5.9 and 5.11, only very low data rates will be supported in this region for transponders 2 and 4. For transponder 3, the TIP injected spot beam, the full data rate will only be supported with the higher FOM receiver.

Transponder 2

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.85	dB
Rain Loss	4.53	dB
Atmoshperic Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.85	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.63	dB
Rain Loss	6.35	dB
Atmospheric Loss	2.67	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	13.10	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	74.72	sB-Hz
C/N0 Total	74.62	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	0.89	dB
Required Eb/N0	6.50	dB
Margin	-5.61	dB

Transponder 3

UPLINK		
EIRP	78.00	dBW
Free Space Loss	214.05	dB
Rain Loss	12.38	dB
Atmospheric Loss	1.39	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	80.33	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.66	dB
Rain Loss	6.40	dB
Atmoshperic Loss	2.83	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	13.09	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	77.30	sB-Hz
C/N0 Total	75.55	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	7.64	dB
Required Eb/N0	6.50	dB
Margin	1.14	dB

Transponder 4

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.90	dB
Rain Loss	4.55	dB
Atmospheric Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.78	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.70	dB
Rain Loss	6.48	dB
Atmoshperic Loss	2.96	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	13.08	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	64.67	sB-Hz
C/N0 Total	64.66	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	2.77	dB
Required Eb/N0	6.50	dB
Margin	-3.73	dB

Table 5.3: UFO 9 Link Budgets for the central Caribbean; transponders 2-4, 22 inch receive antenna, 1.4 dB noise figure, 1% annual rainfall.

Transponder 2

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.85	dB
Rain Loss	4.53	dB
Atmoshperic Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.85	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.63	dB
Rain Loss	6.35	dB
Atmospheric Loss	2.67	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	10.38	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	72.00	sB-Hz
C/N0 Total	71.94	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	-1.78	dB
Required Eb/N0	6.50	dB
Margin	-8.28	dB

Transponder 3

UPLINK		
EIRP	78.00	dBW
Free Space Loss	214.05	dB
Rain Loss	12.38	dB
Atmospheric Loss	1.39	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	80.33	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.66	dB
Rain Loss	6.40	dB
Atmoshperic Loss	2.83	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	10.37	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	74.58	sB-Hz
C/N0 Total	73.56	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	5.65	dB
Required Eb/N0	6.50	dB
Margin	-0.85	dB

Transponder 4

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.90	dB
Rain Loss	4.55	dB
Atmospheric Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.78	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.50	dB
Rain Loss	6.48	dB
Atmospheric Loss	1.48	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	10.36	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	62.15	sB-Hz
C/N0 Total	62.14	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	0.26	dB
Required Eb/N0	6.50	dB
Margin	-6.24	dB

Table 5.4: UFO 9 Link Budgets for the central Caribbean; transponders 2-4, 18 inch receive antenna, 2.5 dB noise figure, 1% annual rainfall.

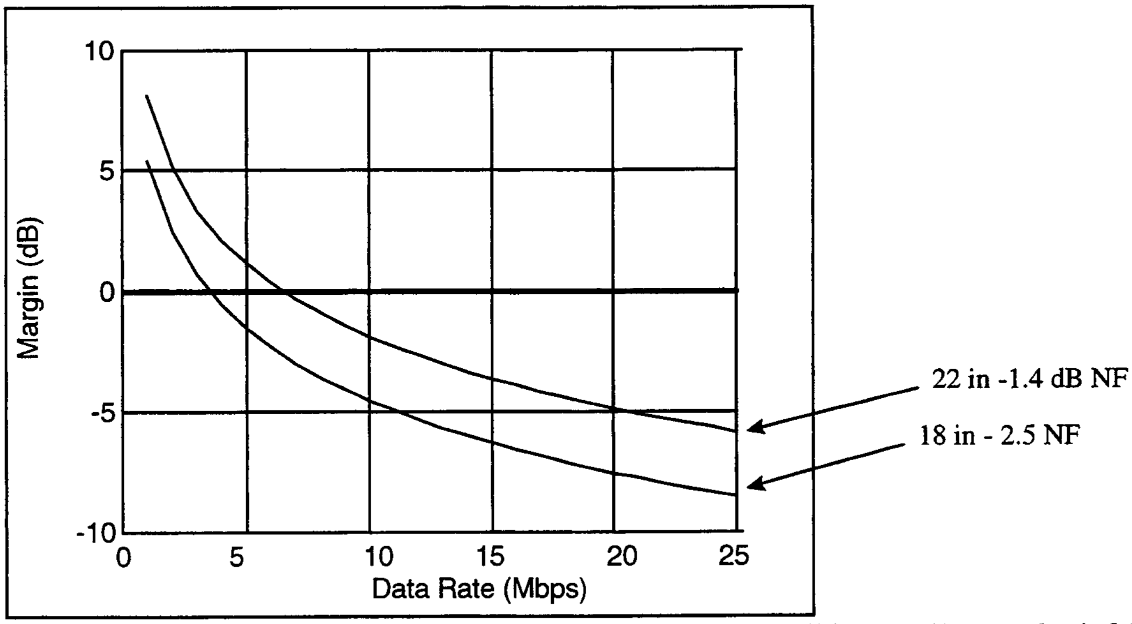

Figure 5.9: Supportable data rates for transponder 2 for the Caribbean; 1% annual rainfall.

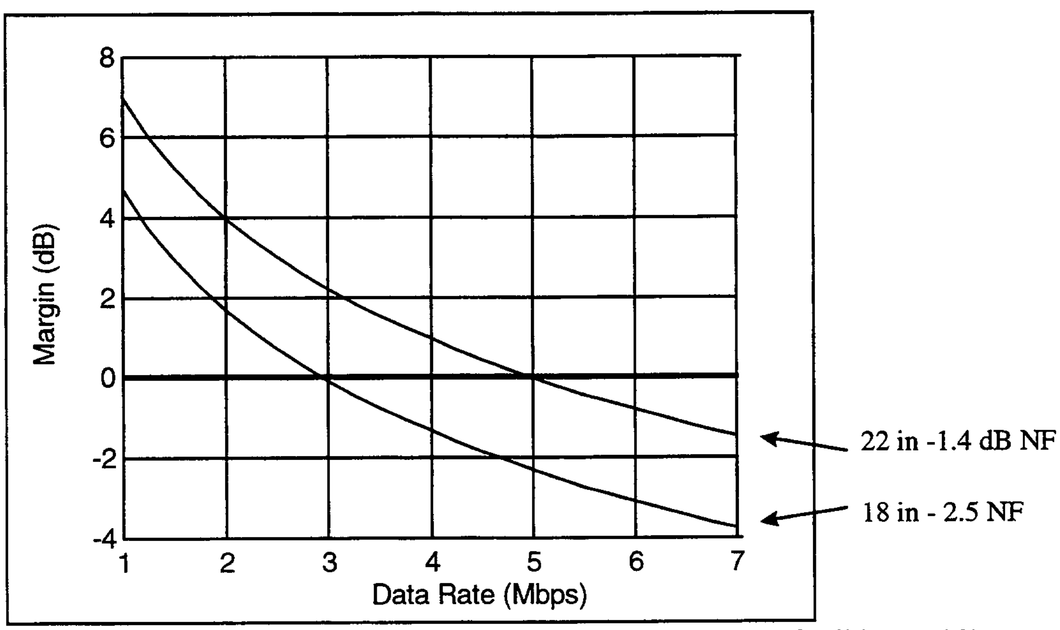

Figure 5.10: Supportable data rates for transponder 3 for the Caribbean; 1% annual rainfall.

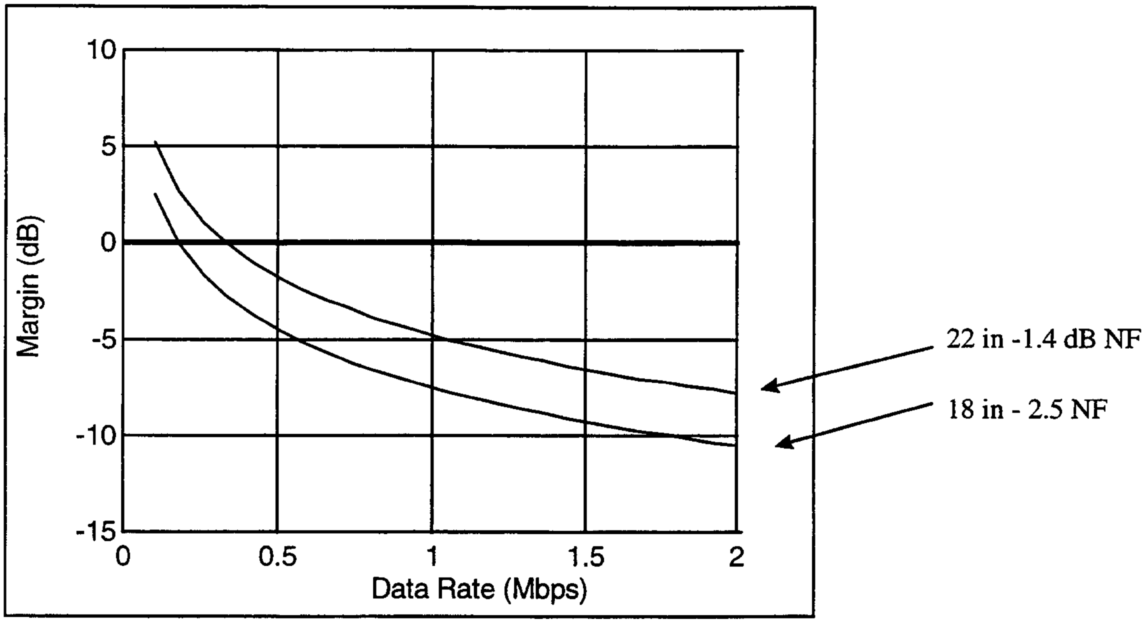

Figure 5.11: Supportable data rates for transponder 4 for the Caribbean; 1% annual rainfall.

As the supportable data rates for the Caribbean are so low when accounting for rain on the up and down-link, it begs the question as to what are the supportable data rates with no rain on the down-link. As can be seen from Figures 5.12 and 5.13, UFO 9 will support the full data rate for the higher FOM receiver, but will only support less than 20 Mbps for transponder 2 and around 1.2 Mbps for transponder 4 for the lower FOM receiver with no rain on the down link.

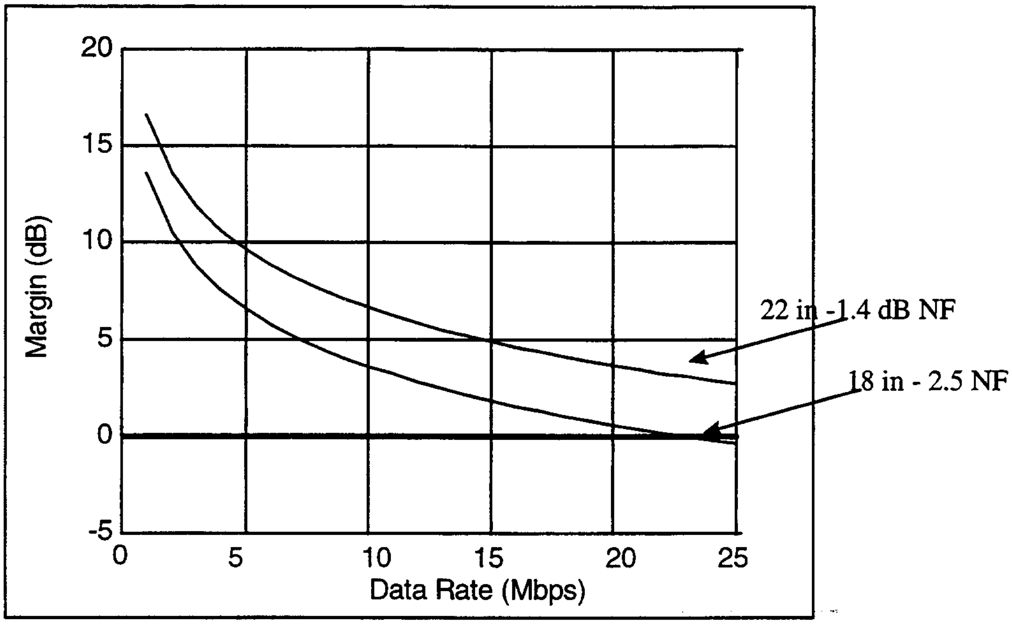

Figure 5.12: Supportable data rates for transponder 2 for the Caribbean; no rain on the down-link.

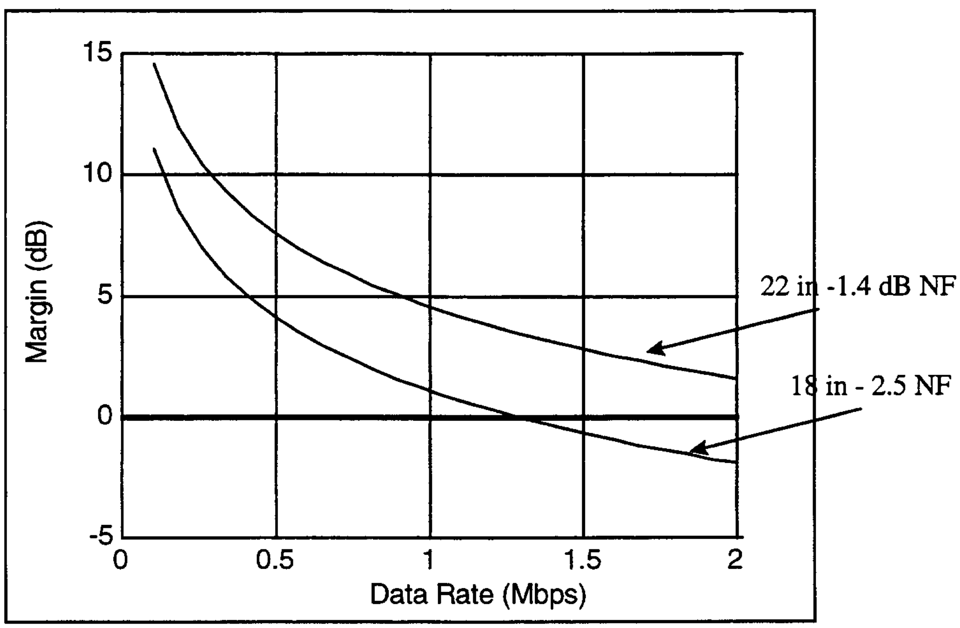

Figure 5.13: Supportable data rates for transponder 4 for the Caribbean; no rain on the down-link.

D. SUPPORTABLE DATA RATES FOR THE ARABIAN GULF

The Arabian gulf has an average water vapor content greater than 20 g/m3 for August. When the UFO 9 antenna boresite is aimed at 26 34.8N/51 03.6E, the elevation angle ranges from 8.77 to 3.17 degrees, with a corresponding atmospheric loss from 4.18 to 11.02 dB. The TIP is assumed to be located in Bahrain, with an elevation angle ranging from 8.6 to 3.3 degrees with a corresponding atmospheric loss of 2.7 to 6.85 dB.

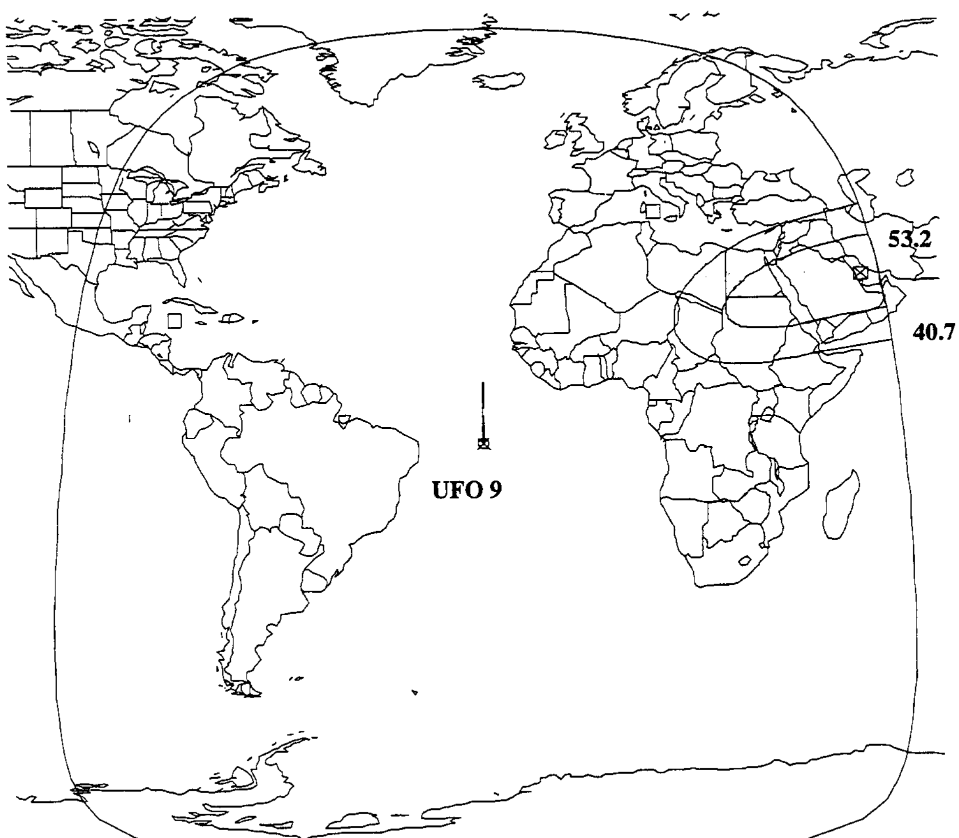

Figure 5.14: UFO 9 spot beam and area coverage beam focused on the Arabian Gulf.

Because the atmospheric losses are so high, UFO F9 will support only very low data rates for all channels for either receiver. This is not surprising as the Arabian Gulf is very close to the absolute edge of UFO F9's coverage. Exacerbating the problem is the fact that this region has such a high water vapor content and, due to the low latitude, the altitude of the isotherm is also high.

Transponder 2

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.85	dB
Rain Loss	4.53	dB
Atmoshperic Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.85	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.97	dB
Rain Loss	3.20	dB
Atmospheric Loss	11.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	13.84	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	69.94	sB-Hz
C/N0 Total	69.91	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	-3.82	dB
Required Eb/N0	6.50	dB
Margin	-10.32	dB

Transponder 3

UPLINK		
EIRP	78.00	dBW
Free Space Loss	214.38	dB
Rain Loss	7.14	dB
Atmospheric Loss	6.85	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	79.78	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.97	dB
Rain Loss	3.20	dB
Atmoshperic Loss	11.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	13.84	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	69.94	sB-Hz
C/N0 Total	69.51	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	1.60	dB
Required Eb/N0	6.50	dB
Margin	-4.90	dB

Transponder 4

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.90	dB
Rain Loss	4.55	dB
Atmospheric Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.78	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	211.00	dB
Rain Loss	3.26	dB
Atmoshperic Loss	11.83	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	13.82	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	56.50	sB-Hz
C/N0 Total	56.50	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	-5.39	dB
Required Eb/N0	6.50	dB
Margin	-11.89	dB

Table 5.5: UFO 9 Link Budgets for the Arabian Gulf; transponders 2-4, 22 inch receive antenna, 1.4 dB noise figure, 1% annual rainfall.

Transponder 2

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.85	dB
Rain Loss	4.53	dB
Atmoshperic Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.85	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.97	dB
Rain Loss	3.20	dB
Atmospheric Loss	11.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	10.95	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	67.05	sB-Hz
C/N0 Total	67.03	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	-6.69	dB
Required Eb/N0	6.50	dB
Margin	-13.19	dB

Transponder 3

UPLINK		
EIRP	78.00	dBW
Free Space Loss	214.38	dB
Rain Loss	7.14	dB
Atmospheric Loss	6.85	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	79.78	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.97	dB
Rain Loss	3.20	dB
Atmoshperic Loss	11.00	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	10.95	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	67.05	sB-Hz
C/N0 Total	66.83	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	-1.08	dB
Required Eb/N0	6.50	dB
Margin	-7.58	dB

Transponder 4

UPLINK		
EIRP	84.00	dBW
Free Space Loss	213.90	dB
Rain Loss	4.55	dB
Atmospheric Loss	0.92	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	90.78	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	211.00	dB
Rain Loss	3.26	dB
Atmoshperic Loss	11.83	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	10.94	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	53.62	sB-Hz
C/N0 Total	53.62	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	-8.27	dB
Required Eb/N0	6.50	dB
Margin	-14.77	dB

Table 5.6: UFO 9 Link Budgets for the Arabian Gulf; transponders 2-4, 18 inch receive antenna, 2.5 dB noise figure, 1% annual rainfall.

As the margins for transponder 4 are so small, only supportable data rates for transponders 2 and 3 are shown (see Figures 5.15 and 5.16). UFO 9 will not support high enough data rates for the Arabian Gulf to justify dedicating the UFO 9 GBS beams to this area. This region should be supported by UFO 10.

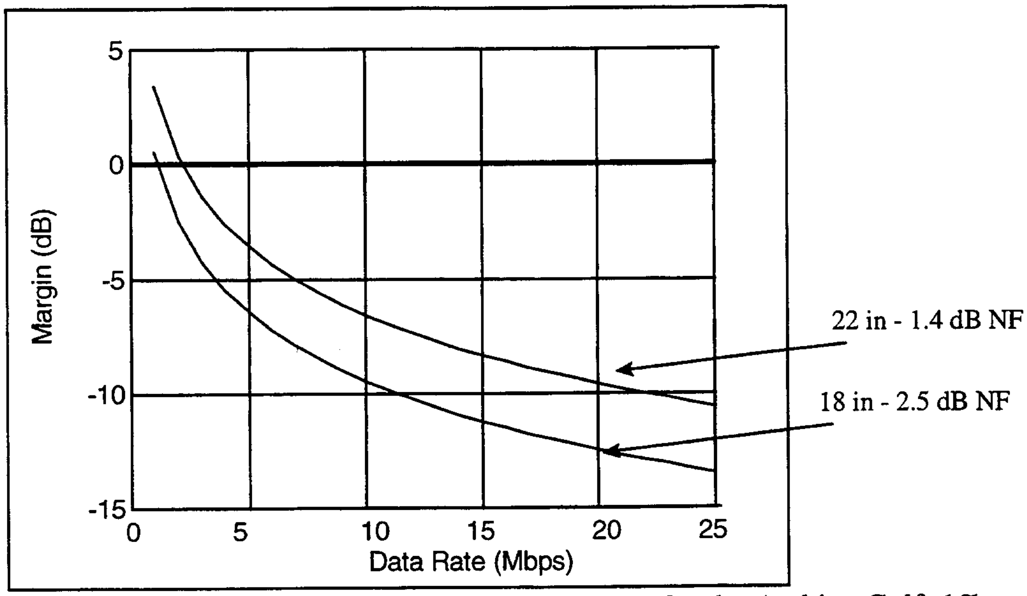

Figure 5.15: Supportable data rates for transponder 2 for the Arabian Gulf; 1% annual rainfall.

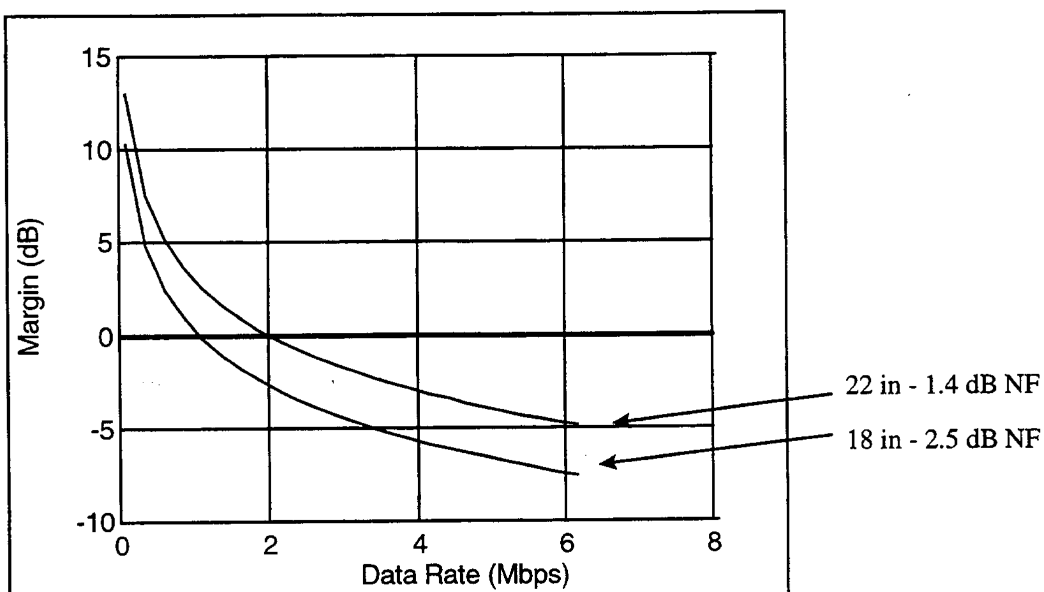

Figure 5.16: Supportable data rates for transponder 3 for the Arabian Gulf; 1 % annual rainfall.

E. SUPPORTABLE DATA RATES FOR THE ARABIAN GULF USING UFO 10

The UFO 10 supportable data rates for the Arabian Gulf will be considerably better than those supportable by UFO 9. As previously mentioned, the Arabian Gulf is very close to the edge of UFO 9's coverage. The Arabian Gulf is relatively close to the center of coverage for UFO 10. (see Figure 5.17)

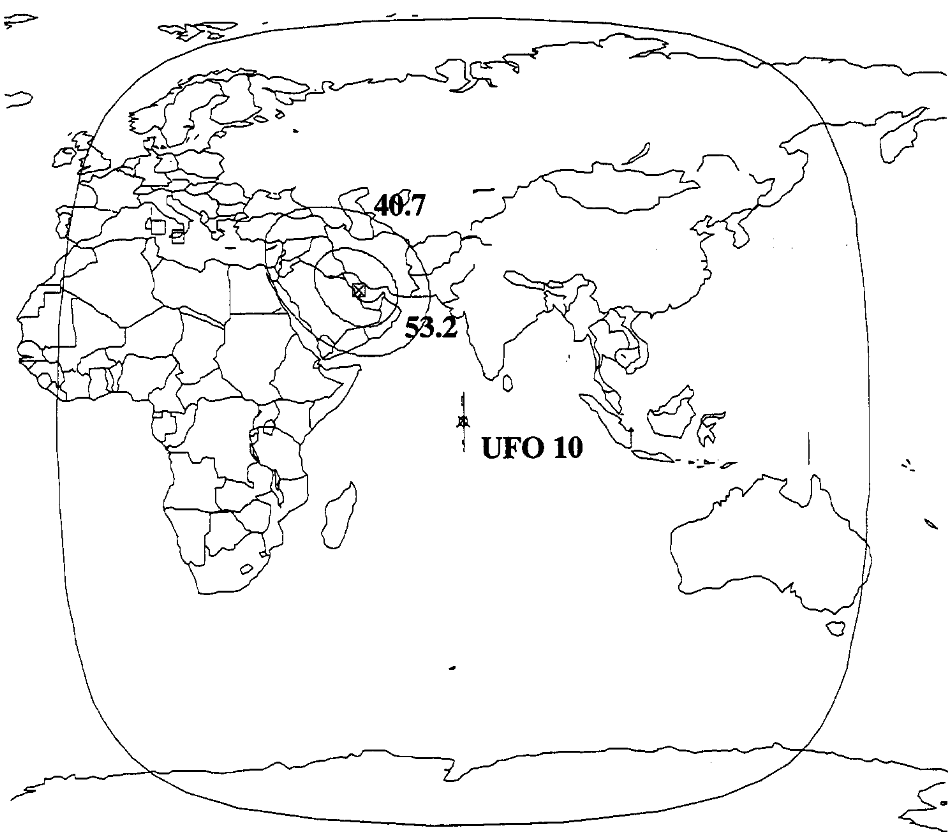

Figure 5.17: UFO 10 spot beam and area coverage beam focused on the Arabian Gulf.

With UFO 10 located at 72E, the receiver elevation angle from the center of the gulf ranges from 56 to 45 degrees with a corresponding atmospheric absorption loss of .77 to .89 dB for the channel 2 down-link. The following link budgets assume that the UFO 10 PIP is also located at Sigonella, with an elevation angle from the PIP to UFO 10 ranging from 21.4 to 12.98 degrees, with a corresponding atmospheric loss of 1.1 to 1.84 dB. The TIP, located in Bahrain, has an elevation angle from 57.7 to 46.8 degrees with a

corresponding atmospheric loss from .63 to .37 dB. As can be seen from Tables 5.7 and 5.8, UFO 10 will support the full data rate for all channels for the higher FOM receiver and will almost support the full data for the lower FOM receiver.

Transponder 2

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.15	dB
Rain Loss	6.28	dB
Atmoshperic Loss	1.84	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	87.88	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.10	dB
Rain Loss	1.07	dB
Atmospheric Loss	0.90	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	14.96	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	84.16	sB-Hz
C/N0 Total	82.63	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	8.90	dB
Required Eb/N0	6.50	dB
Margin	2.40	dB

Transponder 3

UPLINK		
EIRP	78.00	dBW
Free Space Loss	213.49	dB
Rain Loss	2.70	dB
Atmospheric Loss	0.73	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	91.23	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.12	dB
Rain Loss	1.08	dB
Atmoshperic Loss	0.92	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	14.95	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	84.10	sB-Hz
C/N0 Total	83.33	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	15.42	dB
Required Eb/N0	6.50	dB
Margin	8.92	dB

Transponder 4

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.20	dB
Rain Loss	6.35	dB
Atmospheric Loss	1.84	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	87.76	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.17	dB
Rain Loss	1.10	dB
Atmoshperic Loss	0.96	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	14.94	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	71.48	sB-Hz
C/N0 Total	71.38	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	9.49	dB
Required Eb/N0	6.50	dB
Margin	2.99	dB

Table 5.7: UFO 10 Link Budgets for the Arabian Gulf; transponders 2-4, 22 inch receive antenna, 1.4 dB noise figure, 1% annual rainfall.

Transponder 2

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.15	dB
Rain Loss	6.28	dB
Atmoshperic Loss	1.84	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	87.88	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.10	dB
Rain Loss	1.07	dB
Atmospheric Loss	0.90	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	11.77	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	80.97	sB-Hz
C/N0 Total	80.17	dB-Hz
Data Rate (Mbps)	2.36E+07	
Data Rate dB-bps	73.73	dB-Mbps
Achieved Eb/N0	6.44	dB
Required Eb/N0	6.50	dB
Margin	-0.06	dB

Transponder 3

UPLINK		
EIRP	78.00	dBW
Free Space Loss	213.49	dB
Rain Loss	2.70	dB
Atmospheric Loss	0.73	dB
Polarization Loss	0.20	dB
G/T (FOM)	1.75	dBK
Boltz	228.60	dBW/Hz/K
C/N0	91.23	dB-Hz
DOWN LINK		
EIRP	53.20	dBW
Free Space Loss	210.12	dB
Rain Loss	1.08	dB
Atmoshperic Loss	0.92	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	11.77	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	80.92	sB-Hz
C/N0 Total	80.53	dB-Hz
Data Rate (Mbps)	6.18E+06	
Data Rate dB-bps	67.91	dB-Mbps
Achieved Eb/N0	12.62	dB
Required Eb/N0	6.50	dB
Margin	6.12	dB

Transponder 4

UPLINK		
EIRP	84.00	dBW
Free Space Loss	214.20	dB
Rain Loss	6.35	dB
Atmospheric Loss	1.84	dB
Polarization Loss	0.20	dB
G/T (FOM)	-2.25	dBK
Boltz	228.60	dBW/Hz/K
C/N0	87.76	dB-Hz
DOWN LINK		
EIRP	40.70	dBW
Free Space Loss	210.17	dB
Rain Loss	1.10	dB
Atmoshperic Loss	0.96	dB
Pointing Loss	0.30	dB
Polarization Loss	0.23	dB
G/T (FOM)	11.76	dB/K
Boltz	228.60	dBW/Hz/K
C/N0	68.30	sB-Hz
C/N0 Total	68.25	dB-Hz
Data Rate (Mbps)	1.54E+06	
Data Rate dB-bps	61.89	dB-Mbps
Achieved Eb/N0	6.37	dB
Required Eb/N0	6.50	dB
Margin	-0.13	dB

Table 5.8: UFO 10 Link Budgets for the Arabian Gulf; transponders 2-4, 18 inch receive antenna, 2.5 dB noise figure, 1% annual rainfall.

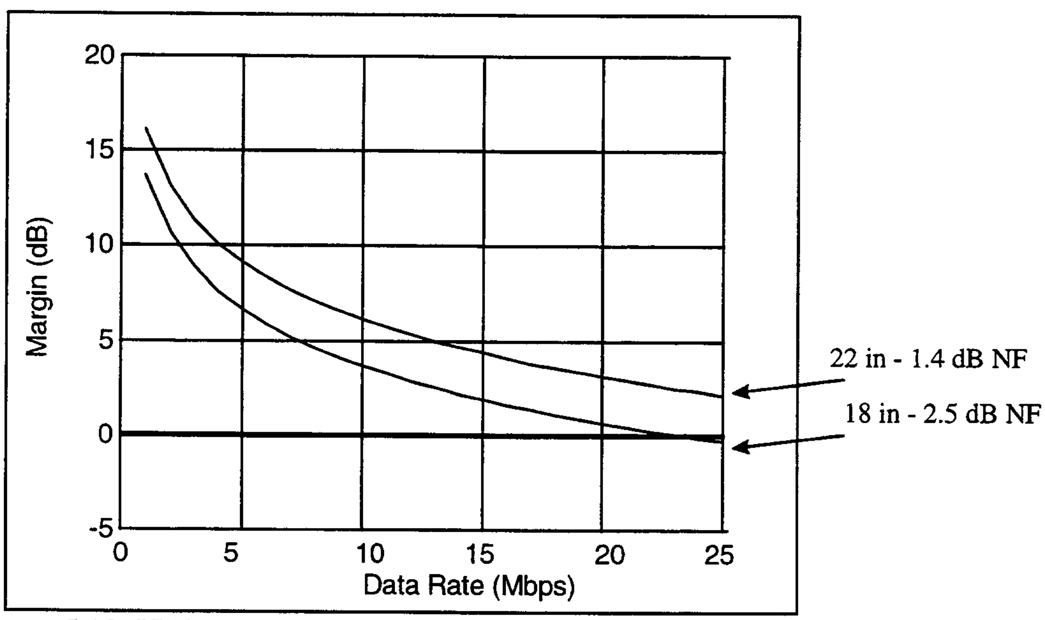

Figure 5.18: UFO 10 supportable data rates for transponder 2 for the Arabian Gulf; 1 % annual rainfall.

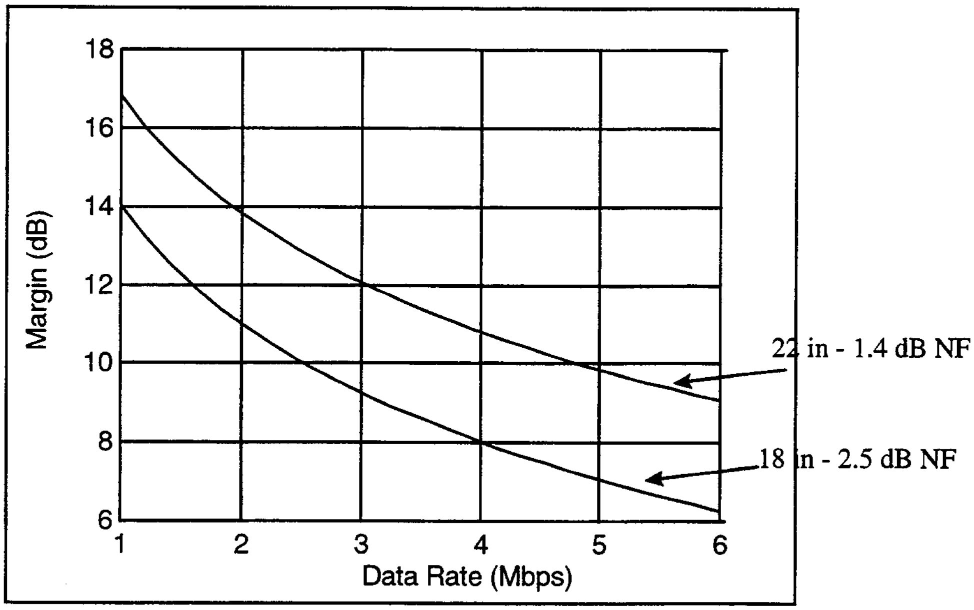

Figure 5.19: UFO 10 supportable data rates for transponder 3 for the Arabian Gulf; 1 % annual rainfall.

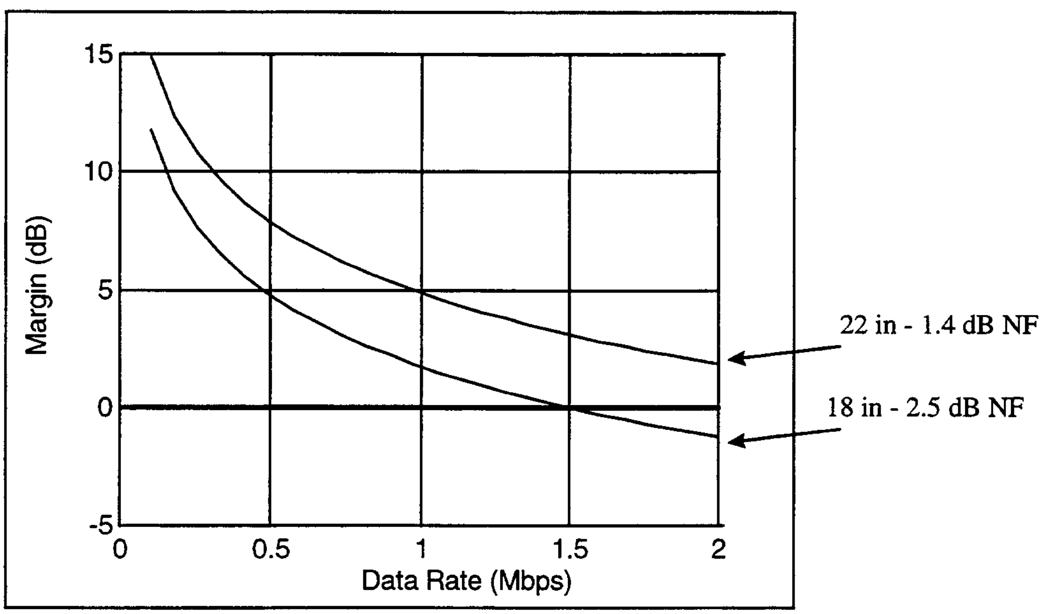

Figure 5.20: UFO 10 supportable data rates for transponder 4 for the Arabian Gulf; 1 % annual rainfall.

F. SUMMARY

This chapter has analyzed supportable data rates for GBS Phase II UFO's 9 and 10 considering worst case atmospheric losses for three significant regions of the world. The atmospheric losses considered were those expected for August, when in the northern hemisphere, water vapor content is at its highest. The analysis also considered the UFO satellite at its furthest distance from the receiver in its daily orbital drift. Because of orbital drift, atmospheric losses can vary by more than 1 dB in a 24 hour period. The EIRP considered for this analysis was not the EIRP expected at antenna boresite. Instead, for the sake of producing conservative estimates, the chosen EIRP was that expected for the edge of coverage for each of the data streams. As was shown, the amount of data that GBS will be able to transmit will depend upon the region of the world in question and the FOM of the receiver. This chapter has shown the necessity for GBS to incorporate an ability to vary its data rate to ensure maximum link closure to critical areas.

VI. CONCLUSIONS AND RECOMMENDATIONS

GBS has considerable potential for delivering large amounts of data to military users who do not have access to terrestrial links. The initial draft of the GBS concept of operations states that GBS will be able to provide high data rates to receivers with small, 18-24 inch, antennas [Ref. 11]. This thesis has shown that the actual deliverable data rates to receivers with small antennas will be limited by environmental losses such as rain and atmospheric absorption. In most cases, GBS will support the full data rate for a receiver with a small antenna with no rainfall loss on the down link. However, with rain on both the up and down-link, GBS must lower its data rate to ensure a 99% link closure. The magnitude of environmental losses will depend on the region in question and the season. In this thesis we only considered regions in the northern hemisphere and August was chosen for the link availability analysis as this is the month when typically water vapor content is highest.

We have shown that the main environmental limitation to GBS supportable data rates is rainfall loss. Determining the magnitude of rainfall loss is a difficult problem as there is no established model for the accurate prediction of rain loss in real time. Rain models that are in use predict rain attenuation as a function of probability of satellite link availability per month or year, given the historical rainfall rates for the region in question. Models currently in use, in particular Crane's Global model and the CCIR model, were developed prior to the widespread use of K/Ka-band RF links. As the Stanford Telecom study has shown, the most accurate model for predicting rain attenuation for K/Ka-band, the USA model, still has a high RMS error: 39.6% for K-band and 32.18% for Ka-band. Furthermore, models designed to predict rainfall loss on an annual basis will have little use for the GBS broadcast manager who may know that rain is expected for a given coverage region on a particular day and needs to accurately know what data rate can be supported. Further study is needed for this sort of data rate management.

I recommend that the GBS testbed at the Naval Postgraduate School (NPS) be utilized for real-time observation of rainfall attenuation. The testbed at the NPS is well located to observe the GBS signal. Assuming one of the UFO 8 spot beams, either transponder 2 or 3, was boresited on San Diego, NPS would be very close to the 53.2 dB EIRP margin of coverage. Utilizing information provided by the meteorological department at NPS the testbed could account for the height of the isotherm and rainfall

rates for the entire rain event, not just for point rainfall measurement. It will be important for the experimenters to know the actual time that UFO 8 crosses the ascending node to ensure accurate estimation of the position of UFO 8. Knowledge of the position of UFO 8 along its orbital drift would ensure the testers were using the correct elevation angle for their measurements. This would give the testers accurate information as to the actual amount of rain along the slant-path. Furthermore, measurements of changing receiver FOM could be determined given the rate of rain actually falling near the antenna. If an adequate number of rain events could be observed, more accurate recommendations for supportable data rates could be made for broadcast managers, given expected rainfall events.

I recommend studying the issue of the BER requirement for GBS. The BER requirement for GBS is set for a "Quasi Error Free" (QEF) quality of 10^{-10}. This requirement is driven by the needs of the MPEG-2 video standard. However, for non-video data transmission, pictures and textual data, a lower BER of 10^{-7} may be tolerable. Transmission of non-video data by GBS may require an Eb/No of only 5.5, one dB lower than what would be required for video data. When rain is expected on the link, broadcast managers could consider not sending video data, or sending a lower quality of video.

My final recommendation concerns the selection of the GBS data transmission standard. There are three options for GBS: the European Digital Video Broadcast (DVB) standard, the Hughes Corporation Direct Satellite System (DSS), or a standard developed specifically for GBS. The GBS Joint Program Management Office (JPMO) released a draft Request For Proposal (RFP) to obtain the industry's views on what standard should be adopted for GBS. The focus was on determining which of the two existing standards was optimum for GBS. There are two important distinctions between the two existing standards. DSS is a proprietary standard that does not allow for varying the data rate. DVB on the other hand is an open standard which allows for varying of the data rate of the video channel.[Ref. 23]

The DVB standard uses QPSK modulation and the concatenation of convolutional and Reed-Solomon codes for forward error correction (FEC). This FEC technique is designed to provide a QEF quality of service for the video channel. QEF means less than one uncorrected error-event per transmission hour, corresponding to a BER of 10^{-10} at the output of the MPEG-2 demodulator. The convolutional code can be configured flexibly, allowing for different code rates to optimize system performance. DVB is optimized for

single carrier per transponder Time Division Multiplex (TDM). It is directly compatible with Motion Picture Experts Group-2 (MPEG-2) coded TV signals.[Ref. 16]

The MPEG-2 standard allows combining many video, audio and data streams into one single data stream. The 24 Mbps spot beam could be used to transmit simultaneously two 9 Mbps video channels and 93 64 Kbps data channels. A 9 Mbps video channel is comparable to studio production quality. However, with MPEG-2, the bit rate utilized for a video channel can be selected freely, depending upon requirements. Typical bit rates for video channels are:

2 Mbps:	approx. VHS quality
4-6 Mbps:	approx. PAL quality
8-9 Mbps:	studio production quality (e.g., for cinema films and sport events)
>15 Mbps:	various levels of HDTV quality [Ref. 3].

DVB allows for five different convolutional code rates: 1/2, 2/3, 3/4, 5/6, or 7/8 rate. A 1/2 code rate means that for every data bit there is an error correction bit. This rate is the most robust convolutional code for error correction but requires the most bandwidth. With DVB the actual Eb/No required for the link budget is dependent upon the convolution code rate as shown in Table 6.1.[Ref. 3]

Inner convolutional code rate	Required Eb/No
1/2	4.5
2/3	5.0
3/4	5.5
5/6	6.0
7/8	6.4

Table 6.1: Required Eb/No for various convolutional code rates.[Ref. 3]

By adopting the DVB standard for GBS it is possible to reduce the data rate for video channels to a lower quality to ensure connectivity in inclement weather. For a 1/2 rate convolutional code, DVB will support data rates from 38.8 to 18.7 Mbps [Ref. 18]. As DVB allows for selectivity in both the code rate and the data rate, this appears to be a good choice for GBS.

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